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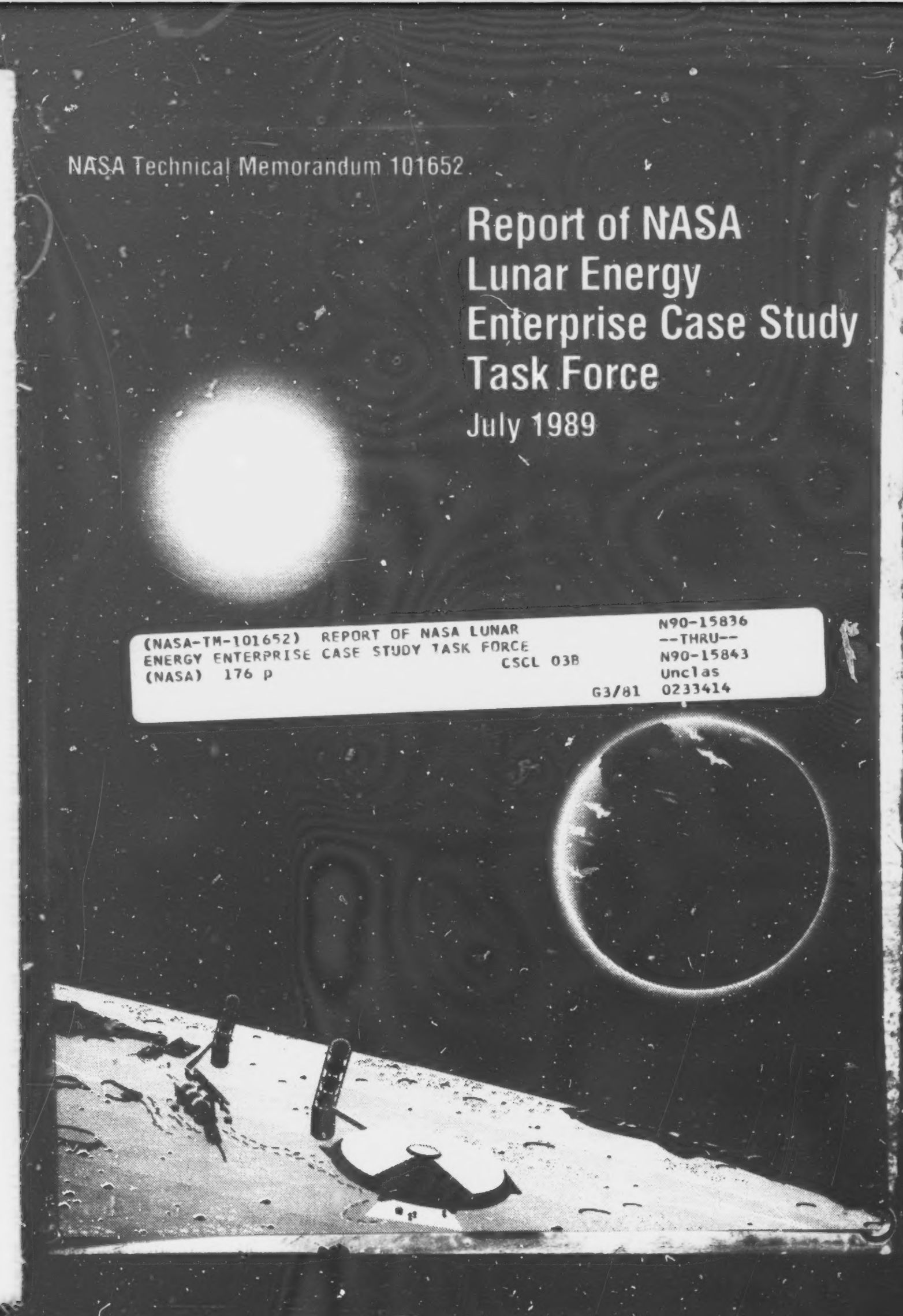

TABLE OF CONTENTS

Page

Table of Contents I

List of Appendixes II

List of Tables III

List of Figures IV

Executive Summary 1

Background 7

Discussion 8

A. Legal Liability Aspects 9
B. Long-Range Electricity Needs 10
C. Futures - America's Economic Imperative 11
D. Long-Range Electricity Supply Options 11
E. Extraterrestrial Electricity Supply Options 14

1. Helium-3 System Concept 15
2. The Solar Power Satellite (SPS) Concept 17
3. Lunar Power System Concept 20

F. Commercial Potential 22

Conclusions 30

Recommendation 32

Appendixes 38

LIST OF APPENDIXES

Page

Appendix A Membership Listing of Lunar Energy Enterprise Case Study Task Force 38

Appendix B-1 Analysis of the Financial Factors Governing the Profitability of Lunar Helium-3 40

G. L. Kulcinski, H. Thompson, S. Ott
University of Wisconsin

Appendix B-2 Introduction to D-^{3}He Fusion Reactors 56

G. C. Vlases
University of Washington
Consultant, Spectra Technology, Inc.

and

L. C. Steinhauer
Spectra Technology, Inc.

Appendix B-3 The Solar Power Satellite (SPS) - Progress So Far 67

P. E. Glaser
Vice President
Arthur D. Little, Inc.
Cambridge, MA, USA

***Appendix B-4** Lunar Power System 84
Summary of Studies for the Lunar Enterprise Task Force
NASA - Office of Exploration

D. R. Criswell
University of California, San Diego

Appendix B-5 Transportation and Operations Aspects of Space Energy Systems 97

G. R. Woodcock
Boeing Aerospace

Appendix B-6 Importance of Helium-3 for the Future 150

G. L. Kulcinski
University of Wisconsin

*Permission to reproduce Appendix B-4 as part of this report has been given by the author.

LIST OF TABLES

			Page
Appendix B-2	Table 1	Advantages/Disadvantages of D - T and D-^{3}He Cycles	63
	Table II, Part 1	Comparison of D-^{3}He Tokamak and FRC Reactor Parameters: Power Flow Characteristics	66
	Table II, Part 2	Comparison of D-^{3}He Tokamak and FRC Reactor Parameters: Plasma and Facility Size Parameters	67
Appendix B-3	Table I	SPS Development Goals	83
Appendix B-4	Table 1	Major Parameters for Modeling LPS Production and Operation	89
	Table 2	Reference and Advanced Technology Levels	90
	Table 3	Scale of 300 GW Power Systems Over 70 Years and Gross Energy Produced Over 70 Years	93
Appendix B-6	Table 1	Reserves of He3 That Could Be Available in the Year 2000	160
	Table 2	Helium-3 Content of Lunar Regoliths	163

LIST OF FIGURES

			Page
	Figure 1	Concept Description of Helium-3 From the Moon	35
	Figure 2	Concept Description of Solar Power Satellites	36
	Figure 3	Concept Description of Lunar Power System	37
Appendix B-2	Figure 1	Schematic of Tokamak Reactor Core	64
	Figure 2	Schematic of FRC Reactor Core	65
Appendix B-3	Figure 1	Power Beaming Growth Path	82
Appendix B-4	Figure 1	Major Components of the Lunar Power System	84
	Figure 2	LPS Capacity and Revenue	85
	Figure 3	Montage: Beaming Power from Moon to Earth and LPS Demonstration Base.	87
	Figure 4	LPS Expenditures for Reference System	91
	Figure 5	Net Profit Versus Inflation	92
	Figure 6	Net Profit Versus Maintenance	92
Appendix B-6	Figure 1	Major Fusion Fuel Reactivities	152
	Figure 2A	Steady Progress toward DT Fusion	153
	Figure 2B	The Progress Toward Energy Breakeven Conditions.	153
	Figure 3	Actual Release of Thermonuclear Energy in the Laboratory.	153
	Figure 4	The Percent of Thermonuclear Energy Released in the Form of Neutron.	155
	Figure 5	A Comparison of Overall Conversion Efficiencies of Nuclear Energy to Electricity.	155

LIST OF FIGURES, CONTINUED

			Page
Appendix B-6	Figure 6	Historical Capital Costs of Commercial Fusion Reactor Designs.	159
	Figure 7	Range of Helium Concentration Measured in U.S. Apollo and USSR Luna samples.	164
	Figure 3	Evolution of He3 From Lunar Regolith	164
	Figure 9	Design of Lunar Vehicle to Extract He3 from Regolith Using Direct Solar Radiation.	165
	Figure 10	Byproducts of Lunar Helium 3 Mining	167

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REPORT OF

THE NASA LUNAR ENERGY ENTERPRISE CASE STUDY TASK FORCE

EXECUTIVE SUMMARY

The Lunar Energy Enterprise Case Study Task Force was asked by NASA to determine the economic viability and commercial business potential of mining and extracting He-3 from the lunar soil, and transporting the material to Earth for use in a fusion reactor to generate electricity. While the Task Force concentrated its efforts on the He-3 concepts, two other space energy projects, the Space Power Station (SPS) and the Lunar Power Station (LPS), were also reviewed because of several interrelated aspects of these projects, such as the use of lunar material, the possibility of manufacturing some elements of the project systems on the Moon, and the need of all three projects for space transportation and space station requirements, in varying degrees. Additionally, the SPS and LPS projects have the capability of providing energy for lunar-based activities.

In carrying out its assignment, the Task Force considered:

1. The legal and liability aspects of the He-3 and other space energy projects.
2. The long-range need for electricity and the energy options to meet these requirements.

3. The state of knowledge of the He-3 and other space energy projects and the time frame for their development.
4. The commercial potential of the He-3 and other space energy projects, and the role industry might be willing to play in their development and use.

The information made available to the Task Force by NASA and other sources suggested no inhibiting legal and liability factors which would prevent the use of Moon resources for the space energy projects. But further study is recommended. While the Task Force did not develop any long-range global electricity forecasts, and while such long-range judgments are difficult to make with a high degree of accuracy, there appears to be general agreement that the use of electricity will continue to increase, particularly in developing countries if they are to raise the standard of living of their citizens. Thus the need to examine long-range electricity options is essential. Most electricity growth will be met in the next several decades by utilizing current technology and terrestrial fuel resources, particularly in developing nations. But long-term, there could be limitations in the use of our current means of producing electricity, as emerging environmental concerns and resource availability suggest a changing character to the energy policy decisions that must be

made in the future. Environmental concerns have momentum, and, if nothing else, they have the potential to increase the real costs of producing electricity with the use of fossil fuels as resources become more expensive to produce (particularly oil and gas) and the capital cost of the facilities to burn fossil fuels (particularly coal) in an increasingly strict environmentally acceptable manner becomes more expensive. These cost factors make serious consideration of extraterrestrial energy options a matter of national interest. Synergism with future space policy directions may also be a factor that would influence future energy supply choices. Long-term global ecological concerns cannot be quantified nor can the long-term production costs of current, or as yet developed energy options, but it is, nevertheless, important to have these additional options. The Moon can provide these. All three options considered in this Report (He-3, LPS and SPS) have the potential promise to provide a practically inexhaustible, clean source of electricity for the U.S. and worldwide, without major adverse impacts on the Earth's environment.

Total industry responsibility for pursuing any of the three extraterrestrial energy concepts considered in the Report is not possible at this time because the risk is high; the payout period is long; technological feasibility is not fully developed, and thus requires considerable R&D investment; and near-term energy

investments are more attractive. Pursuit of these energy concepts requires the combined efforts of government and industry. Indeed, total and sole government responsibility would inhibit progress. Innovative forms of government and industry cooperation must be developed and implemented over the next several decades. The Report describes one such innovative approach. There are probably others which further detailed analyses by financial experts might suggest. The arrangement outlined in the Report is based on the conviction that the commercial development of extraterrestrial energy and the development of a lunar base can be linked effectively. The lunar base can serve as a development step of many of the technologies needed for the energy system, and can be a customer for services at pilot production levels.

The Moon must play a role in long-term terrestrial electricity supply matters. Early commercial involvement in this task is of paramount importance in achieving this objective and a meaningful leadership role for industry is potentially possible. But total industry responsibility for projects of this financial magnitude is not initially possible and government involvement through subsidies or other means, such as co-funding or enabling contracts, is vital. The mining of He-3 for transportation to Earth is a potentially viable, economic concept but understandbly

on a long-range schedule and subject to government/industry cooperative arrangements outlined in the Report. The two solar power concepts likewise could have long-range economic potential as extraterrestrial electric power sources but the three concepts were not rated in terms of potential economic viability, although it is evident that each concept has both promise and problems.

The factual case for the Report's findings needs further development. NASA and DOE should continue to support studies that will better frame the development of the projects and provide the additional technical, economic and financial information that will be necessary for greater commitments. These studies, however, should not be contracted for under normal government procedures. Industry should be given a primary role in planning the overall program, perhaps through the establishment of a high-level private sector advisory committee. High-level representatives of the Administration, appropriate government agencies such as DOE, EPA and NASA, the energy, environment and space leadership of the Congress, electric utilities, the space and energy supply industries, and the financial community must consider looking beyond Earth for our long-term electricity needs because of potential damaging ecological impacts with continual major dependence on fossil fuels for terrestrial energy needs. This is a revolutionary concept, and is based on a crucial

observation regarding long-term environmental consequences of our current energy production options. There must be understanding, agreement and long-term commitment, and the national will to implement the commitment as a matter of national policy.

Lastly, we must recognize that other nations, notably Japan, West Germany and Russia, are proceeding with very aggressive programs to investigate and develop space-oriented, energy systems. It will be done. It is just a matter of by whom.

REPORT OF

THE NASA LUNAR ENERGY ENTERPRISE CASE STUDY TASK FORCE

BACKGROUND

The Lunar Energy Enterprise Case Study Task Force (the Task Force), a group of professionals with diverse backgrounds and responsibilities (membership list attached as Appendix A), was asked by NASA to determine the economic viability and commercial business potential of mining and extracting He-3 from the lunar soil, and transporting the material to Earth for use in a fusion reactor to generate electricity. In order to bring perspective to the study, two other extraterrestrial electric energy production projects were considered as "straw men". One was to collect and convert solar energy into electricity and beam it to Earth from a space power station (SPS) and the other from the Moon, a lunar power station (LPS).

While the Task Force concentrated its efforts, in accordance with its NASA charter, on the He-3 concepts, the other two projects were also reviewed because of several interrelated aspects of the projects, such as the use of lunar material, the possibility of manufacturing some elements of the project systems on the Moon, and the need of all three projects for space transportation and space station requirements, in varying degrees. Additionally, the SPS and LPS projects have the capability of providing energy for lunar-based activities.

DISCUSSION

The Task Force has met five (5) times to carry out its responsibilities. In addition, various subgroups of the Task Force have met to consider detailed technical or financial issues. During the course of its study, the Task Force has considered:

1. Legal/Liability Aspects -- can we conform to legal requirements and utilize the Moon in the manner contemplated (i.e., can the laws be adapted to facilitate use of the Moon for an enterprise)? What about compensation for damages? Who will bear the risk?
2. Long-range Need for Electricity -- is there a market for the projects' output?
3. Long-range Electric Generation Options and their Environmental Impact -- can the $He-3$ fusion concept compete? Is it or the other extraterrestrial concepts more compatible with the environment than current terrestrial electric power production facilities?
4. State of Knowledge -- what do we know? What remains to be done? What about costs, etc.?
5. Time Frame of Development -- when might the $He-3$ fusion concept or the other extraterrestrial concepts be capable of reliable performance? How do they, or can they, tie into other NASA programs or objectives?

6. Commercial Potential -- what role would industry be willing to take in the extraterrestrial projects, under what circumstances and when?

Given the limited resources of the Task Force, time constraints and a charge to investigate only whether further detailed study, presumably with adequate resources, should be undertaken, the Task Force in many instances was capable of rendering only qualitative judgments. It has, however, collected or developed significant technical information. The highlights of these data are attached as Appendices B-1, B-2, B-3, B-4, B-5, and B-6 to this Report.

Legal/Liability Aspects - The NASA staff provided the Task Force with a brief verbal report on the legal aspects of a U.S. entity utilizing the Moon for the production of electricity for terrestrial purposes, with a conclusion that it would be possible to do so in a manner that would meet international treaty intents regarding "Benefits to All Mankind". Some members of the Task Force, however, believe that obtaining title to lunar real estate might be necessary to attract venture capital for lunar enterprise projects.

A February 1989 report by the Wisconsin Center for Space Automation and Robotics for the NASA Office of Commercialization

reviewed the He-3 concept and concluded that an acceptable basis can be found for cooperative international production of lunar He-3, should the U.S. decide to do so.

Space treaties also address liability aspects of the projects being considered, specifically stating that government indemnification would be available to cover commercial projects.

The information available to the Task Force, and the expertise of certain members of the Task Force suggest that the legal issue does not appear to be a "show stopper". Nevertheless, further independent study should be undertaken.

Long-Range Electricity Needs - Fully supportable, long-range projections of electricity use (25 to 50 years), particularly on an international basis, are difficult to make. Nevertheless, some observations about the future use of electricity can be made with a high degree of confidence. From 1972 to 1988, U.S. energy use rose by less than seven percent, but electricity use grew by 55 percent. It is expected that in the U.S., electricity will continue to be the energy of choice for end-use purposes and its use, relative to other energy sources for end-use purposes, should continue to increase. Based on an extensive review of economic, societal and technological trends, the Edison Electric Institute* recently issued a report entitled, Electricity

* The Edison Electric Institute is the national association of the investor-owned electric utility industry.

Futures - America's Economic Imperative, which projects that the total U.S. electricity consumption will grow by 2.6 percent annually until the Year 2000, and then by 1.5 percent annually in the 15-year period 2000 to 2015.

In order to increase and sustain economic growth, even greater electricity growth rates must be achieved by developing countries. A 1988 report of the Working Group on Long-Term Forecasting of the Organization for Economic Cooperation and Development (OECD) estimated that electricity projections for the OECD regions (North America, Western Europe and the Industrialized Pacific) would double during the period 1985-2030, while there would be an eight-fold increase in projected electricity usage in the developing countries during the same period. Conservation may work "wonders" in societies where waste exists, but does not solve the energy production needs of the majority of mankind.

Long-Range Electricity Supply Options - Most electricity growth will be met in the next several decades by utilizing current technology and terrestrial fuel resources, particularly in developing nations. For the most part, these will be provided by coal and nuclear fission. But long-term, there could be limitations in the use of our current means of producing electricity. It is beyond the scope of this report to quantify these limitations and when they might influence energy policy at both the national and international levels. But emerging environmental

concerns and resource availability suggest a changing character to the energy policy decisions that must be made in the future. For example, Western European per capita energy consumption applied worldwide would lead to the inane energy consumption of 40,000 million metric tons of coal equivalent per year!* And yet, economic aspirations require increased energy availability particularly to poor countries. Forests are a poor and limited source to meet such needs. And their use as combustible fuels would add to, not decrease, environmental impacts.

We have already seen environmental issues raised to a global level with concerns about global climate change. One of the solutions suggested to mitigate global warming is a reduction in the use of fossil fuels to decrease CO_2 emissions by 20 percent as early as the Year 2000. Only time will tell how urgent is the problem and how Draconian will be the solutions. But the global environmental concerns have momentum, and, if nothing else, they have the potential to increase the real costs of producing electricity with the use of fossil fuels as resources become more expensive to produce (particularly oil and gas) and the capital cost of the facilities to burn fossil fuels (particularly coal) in an increasingly strict environmentally acceptable manner becomes more expensive.

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* According to the 1986 Energy Statistic Yearbook of the United Nations, world consumption of energy in 1986 was 9322 million metric tons of coal equivalent.

Currently, in the United States, nuclear fission is not considered a near-term, viable electricity option for new capacity for several reasons which need not be discussed in this Report. And, although it is, and will continue to be, a viable option in other nations, and, although many believe it will, and should, be a revitalized option in the United States in the near-term future, there is the possibility in the longer-term future that thermal pollution, nuclear proliferation and nuclear waste concerns will continue to impact adversely on its use.

Any development of long-term (25 to 50 years) scenarios of international energy production and use is fraught with problems. It is very difficult to suggest that fossil fuels, and more recently, nuclear fuels, which have served us well and in which governments and industry have huge investments, should not remain, along with conservation and end-use efficiency, the cornerstone of our near-term energy future. The long-term is not so clear.

The only apparent choice with today's technology is coal and nuclear fission power. They will and should be used. Also to be considered is the D·T fusion reactor and Earth-based solar power. But these energy options have drawbacks. The D·T reaction results in radioactivity and Earth-based solar power is limited to cloud free daylight hours of operation. Consequently, it is important to have additional options. The Moon can provide these.

All three options considered in this Report (He-3, LPS and SPS) have the potential promise to provide a practically inexhaustible, clean source of electricity for the U.S. and worldwide, without major adverse impacts on the Earth's environment.

Deep and growing concerns regarding environmental pollution, thermal limits, potential fuel scarcity, and the non-uniform international distribution of fossil resources suggest cost factors that will influence future directions, and make serious consideration of extraterrestrial energy options a matter of national interest. Synergism with future space policy directions may also be a factor that would influence future energy supply choices.

Extraterrestrial Electricity Supply Options - As stated in the background section to this report, NASA requested the Lunar Enterprise Case Study Task Force to assess the economic viability of mining and burning lunar He-3 to produce terrestrial electric power. In order to provide perspective to the assessment, the Task Force was requested to consider two other extraterrestrial electric energy production projects, the solar power satellite (SPS) and the lunar power system (LPS). What follows are brief technical descriptions of the three concepts. More detailed information about the concepts is provided in appendices B-1 to B-4. Appendix B-5 provides additional information on the

space transportation requirements and operations aspects of space energy systems. Appendix B-6 provides additional information on the He-3 concept.

Helium-3 System Concept

According to plans prepared before a source of He-3 was discovered, the first fusion reactors will be fueled by two isotopes of hydrogen, deuterium (D) and tritium (T), to produce energy, neutrons and helium. One of the drawbacks of this process will be the radioactivity which accompanies the neutrons and tritium, orders of magnitude less than from fission reactors, but undesirable nevertheless.

He-3 combines with deuterium in an alternate fusion reaction. This reaction produces fewer and lower energy neutrons and almost no tritium but as much energy as the D·T reaction. Besides generating critical reaction energy and reduced radioactivity, the D·He-3 reaction could ease the development, licensing, and maintenance of fusion reactors. The D·He-3 fusion process produces charged particles. This holds the potential for a large increase in the conversion efficiency to electric power by avoiding the step of thermal conversion. However, compared to the D·T reactor, the D·He-3 reactor may be larger and will operate at a temperature three times as high.

Fusion of He-3 has received little emphasis in the Department of Energy development programs because not enough He-3 was available on Earth to support a commercial reactor. Research and demonstration reactors are feasible with the terrestrial He-3 supply, and the Joint European Tokamak research reactor has already produced 100 KW of D·He-3 thermonuclear power. However, in the early 70's, lunar scientists noted that a large quantity of He-3 had been implanted by the solar wind in the lunar soil and that this He-3 could be used as a fusion fuel. It has been estimated that 25 tonnes of He-3, reacted with D_2, would have provided for the entire U.S. energy consumption in 1987. Although lunar He-3 is not renewable, it is estimated that there is sufficient He-3 on the surface of the Moon to satisfy the world's current electric energy needs for over a 1000 years. Thus, the He-3 concept, shown in Figure 1, involves going to the Moon to separate the He-3 from the lunar soil, and return it to Earth for use as a fuel in specially designed commercial fusion electric power plants.

To achieve this goal, will require large-scale lunar mining, soil processing, and separation of He-3 from other released volatiles, transportation of this helium to Earth, and development of the D·He-3 fusion reactor. Definition of each of these steps has been initiated. A lunar miner which returns soil to the trench after removing volatile substances, including

$He-3$, is in a preliminary conceptual design stage. Separation of $He-3$ from other gases could use available technologies. Volatile by-products, such as hydrogen, oxygen, water, and nitrogen, in quantities much larger than that of $He-3$, will be produced. Important space applications may exist for these materials. Concepts for transporting the $He-3$ to Earth and for fusion reactors to burn it are also being studied.

$He-3$ could sell on Earth for a half million dollars per pound, according to preliminary benefit analyses. This could make $He-3$ an ideal space product worth the expense of the mission. In addition, the accumulation of volatile by-products on the Moon could be worth as much, financially, as production of $He-3$. Thus, in a preliminary sense, the $He-3$ concept appears to have great economic potential.

The Solar Power Satellite (SPS) Concept

The objective of the SPS is to convert solar energy in space for use on Earth. Its most significant benefit is the potential for continuously generating large-scale electric power for distribution on a global basis. The SPS concept is shown schematically in Figure 2.

An SPS system would consist of many satellites in geosynchronous Earth orbit, each SPS beaming power to one or more receiving antennas at desired locations. The system, as studied

by NASA and DOE in the 1970's, provided 5000 Mw of electric power to the Earth from a single satellite. Use of modern structural techniques in a 1990's design would substantially reduce the mass and further enhance SPS feasibility.

Solar radiation received in geosynchronous orbit is available 24 hours a day most of the year. With this year-round power capability, SPS could be used to generate base load power on Earth with a minimum requirement for energy storage.

Microwave beams, or laser beams, would be used to transmit the power generated by the SPS to receivers on Earth. With microwave power transmission, for example, generators are incorporated in the transmitting antenna, which is designed as a circular, planer, active, slotted, phased array. To provide microwave power from geosynchronous orbit, the transmitting antenna would be about 1 kilometer in diameter, and the receiving rectenna on Earth would be about 10 by 13 kilometers, at 40 degrees latitude. The microwave receiving and converting antenna (rectenna) has already been demonstrated to convert a microwave beam into direct current electricity with an efficiency of 85 percent.

To be commercially competitive, the SPS will require a space transportation system capable of placing payloads into low orbit

and geosynchronous orbit at substantial lower cost than possible today. This will require an advanced launch system similar to several now being considered. If SPS power could be supplied on a small scale to evolving space projects, such as Space Station Freedom, overall SPS feasibility may be enhanced.

From a technology viewpoint, SPS does not require a return to the Moon; however, SPS would benefit economically from the establishment of a lunar base and the development of processing technologies for lunar materials. Transportation of all the required materials from Earth on a scale required to build up a global SPS system may result in environmental damage from propulsion by-products. Since less energy is required to move mass from the lunar surface to geosynchronous Earth orbit than from the Earth's surface to the same orbit, it will be advantageous -- potentially even mandatory for economic feasibility -- to obtain materials for the construction of the SPS from the Moon. If processing and the transportation of materials from the Moon to geosynchronous orbit could be accomplished at costs comparable to the launches of payload from Earth, conceivably, more than 90 percent of the mass of an SPS could be mined, refined, fabricated, and transported from the Moon.

In summary, lunar resources, such as metals, glasses, and oxygen, promise to provide materials for the construction of the

system of solar-powered satellites in geosynchronous orbit provided that the use of these resources can be competitive with terrestrial materials. Also, through the SPS reference system study of the 1970's, it has been demonstrated that the technology for transmitting power from space to Earth is amenable to evolutionary development and that the SPS concept is technically feasible. If placed near the Moon, an SPS could provide power to a lunar base as a first, important technology demonstration project of far-reaching importance.

Lunar Power System Concept

The lunar power system (LPS) is a microwave power-beaming concept which uses the Moon rather than Earth-orbiting satellites for collecting and transmitting power. The elements of this system can be understood from Figure 3. The LPS will collect solar energy at lunar power bases located on opposing limbs of the Moon. Each base contains solar converters and microwave transmitters that transform the solar power into microwave power. This is beamed to receivers on Earth and in space, which convert the microwaves back to electric power. Most of the components of the base will be formed from lunar materials. Initial estimates suggest that only one tenth of a tonne of components and consumables will be required from Earth to implace one megawatt of received power.

To use a lunar power base during lunar night, additional sunlight will be reflected to the base by mirrors in orbit about the Moon. Microwave reflectors in mid-altitude, high inclination orbits about the Earth, will redirect microwave beams to rectennas that cannot directly view the Moon. The sunlight and microwave reflectors can eliminate the need for power storage on the Moon or Earth, permit the LPS to follow the power needs of each receiver, and minimize the need for long-distance power transmission lines on Earth. The complete lunar power system consists of the power bases, the orbital mirrors around the Earth and Moon, and the rectennas.

The billboard-like antennae of one LPS base are arranged over an area of the limb of the Moon so that when viewed from the Earth they appear to merge into a single, large, synthetic aperture transmitter with a diameter of 30 to 100 kilometers. The transmitted beams are convergent toward a point well beyond the Earth. Each beam can be intensity-controlled across its cross-sectional area to a scale of 200 meters at the Earth. This allows the LPS to uniformly illuminate rectennas on Earth that are larger than 200 or 300 meters across.

A given base on the Moon is adequately illuminated only about half of the days of the lunar month. It is preferable to keep the lunar bases illuminated and delivering power continuously.

Large mirrors, "Lunettas," will be placed in orbit about the Moon and oriented so as to reflect sunlight to the bases. A "Lunetta," a version of the solar sail, will have low mass per unit area, be of low optical quality, and be constructed primarily of lunar materials.

A station on Earth will receive power directly from the Moon when the Moon is approximately 10 degrees above its local horizon. To provide continuous power to rectennas that are blocked by the Earth or attenuated by long paths through the atmosphere, microwave mirrors in Earth orbit are required. Each microwave mirror will be approximately 1 kilometer in diameter and be continuously oriented so as to reflect the microwave beam from the Moon to a rectenna on Earth.

The lunar power system is complex but has the advantages of enormous power potential, support for both continuous base load and load following power and global coverage. If developed in conjunction with a lunar base, it could supply power to the lunar base as a means of starting the commercialization process.

Commercial Potential - In evaluating the commercial potential of a concept, industry considers many factors including degree of risk, payout period, potential market, technical feasibility, R&D investment requirements and competition of alternative methods.

If these criteria are applied to the end-stages of the He-3 fusion project or other extraterrestrial concepts at this state of their early development, it is not surprising that industry will not invest now in these concepts when compared to other financial opportunities. But the same conclusion was understandably reached about nuclear fission at a similar stage in its development.

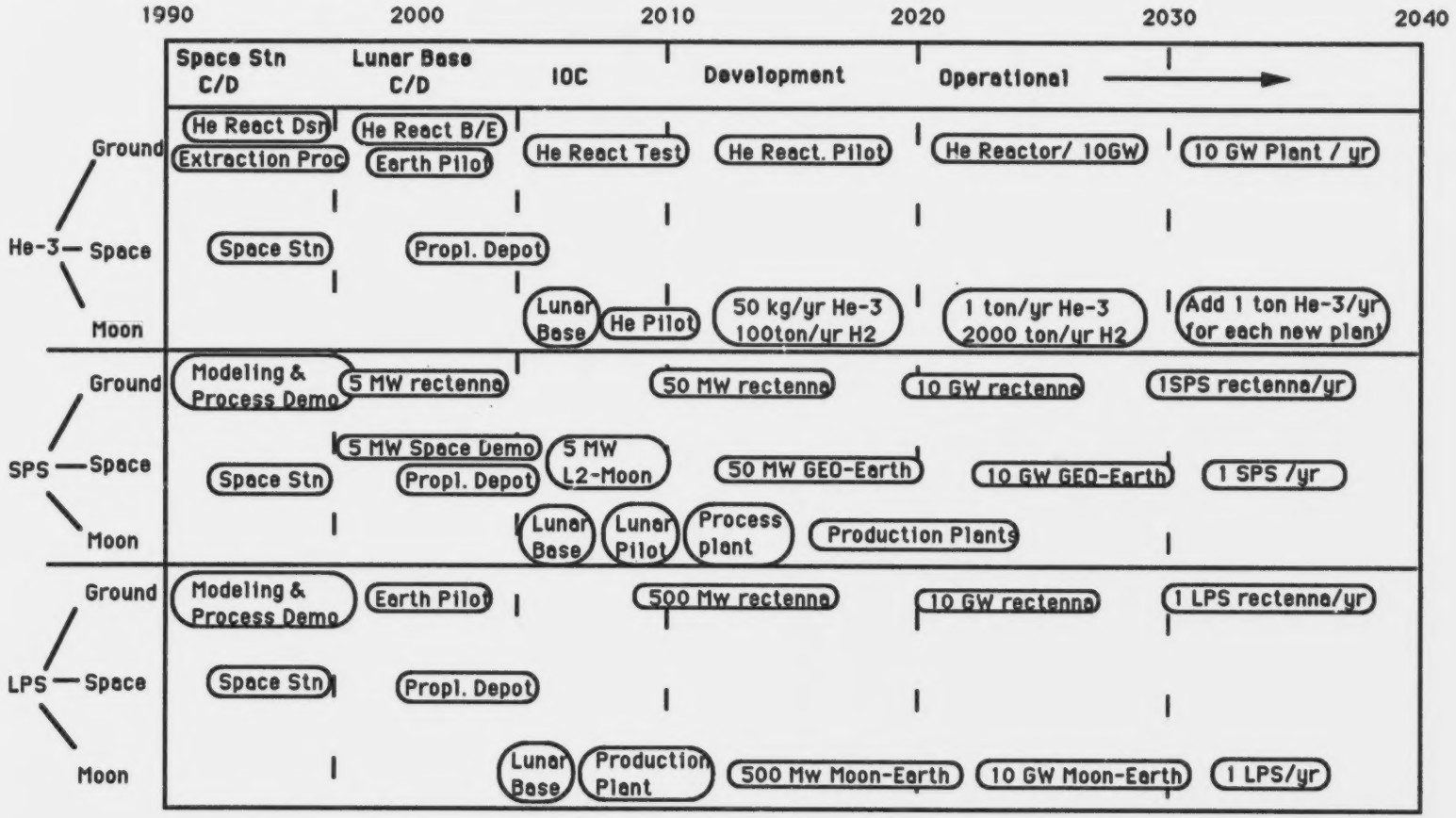
Commercialization of new concepts takes the combined efforts of government and industry. The Task Force believes a similar approach is possible and should be considered in exploring means to develop long-range, terrestrial electricity supply using extraterrestrial resources, principally the Moon. The Japanese government/industry approach, embodied in MITI, has been successful in providing Japan with the means of gaining leadership in many high technology undertakings. This approach should be considered by the U.S. Government and industry in developing extraterrestrial energy supply.

The Task Force also firmly believes that complete government assumption of total project responsibility would inhibit the advantages of commercial involvement. Furthermore, a development program that will evolve over a longtime horizon (50 years) is outside the time horizon normally considered even by very innovative industries and corporations, although it is comparable to

the perspective of some natural resource industries. Yet, extraterrestrial energy projects require such a long-term outlook. Hence, there is an intrinsic need for an innovative approach to the industry and government cooperation. In addition, the long-time horizon (50 years) makes it very questionable to use standard tools of quantitative economic and econometric analysis (prices, technologies, demand, etc.), since they shift significantly and in unpredictable ways.

With these project characteristics and requirements in mind, the Task Force, during the course of its deliberations, discussed the proposed Lunar Outpost, which was briefly described in the NASA Office of Exploration 1988 Annual Report to the NASA Administrator. The review indicated some coincidence between the Lunar Outpost development time scale and those of the $He-_3$ fusion project and the other extraterrestrial energy projects. This is shown on the chart on the following page.

LUNAR BASE AND ENTERPRISE CONCEPTS TIME LINE



The coincidence demonstrated on the chart on the preceding page suggested a possible innovative, government/industry cooperative approach to developing and eventually utilizing extraterrestrial resources to help meet terrestrial energy needs. This approach -- and there probably are others which further detailed analyses by financial experts might suggest -- is based on the conviction that the commercial development of extraterrestrial energy and the development of a lunar base can be linked effectively. The lunar base can serve as a development step of many of the technologies needed for the energy system, and can be a customer for services at pilot production levels.

The three options considered in varying degrees by the Task Force ($He\text{-}3$, LPS, SPS) differ significantly in both the services and side products each may offer for the Lunar Base deployment and subsequent expansion. Solar power technologies can be designed to provide early power services for Lunar Base operations, as well as efficient lunar-Earth transportation. $He\text{-}3$, per se, could provide power only at some distant future time. However, power sources needed for mining, beneficiation, and processing also could provide early power services to a Lunar Base. On the other hand, $He\text{-}3$ mining operations can provide very large amounts of significant side products (H_2, O_2, C, Al, Si, etc.) for lunar and space operations.

Based on these observations, the following opportunity for industry and government cooperation might be considered:

- An industry consortium and NASA could enter into a joint development effort for providing energy/utility services to the Lunar Base, with a view to have early industry involvement also in the RDT&E of any of the three (and potentially other) lunar-based energy options.
- To accomplish this arrangement, innovative legal and statutory forms of long-term cooperation between industry and NASA would have to be explored, ranging from a long-term service contract for providing these services (energy supplies to the Lunar Base and later production of energy for use on Earth and in Space), combined with possible co-funding of RDT&E on critical technology components, to rights of first refusal to any intellectual and patent rights developed as a result of this development effort.
- In addition, the opportunity for industry involvement would be improved with a streamlining of government supervision, regulation, duplication of administrative and accounting functions. The consortium should be entrusted with the procurement of necessary technology components, and the examination of options and alternatives within each of the key technologies.*

* The precedent set in the development of commercial space communications by the COMSAT Act may be followed.

- An important key to lowering the public cost to this enterprise would be the granting of mining concessions and rights to the extracted resources to the consortium. Innovative international legal precedents also may have to be established.
- The By-Laws of the consortium would provide for a "plowback" of part of the revenues from the sale of service to NASA and technology advances to benefit the enterprise effort.

Assuming that such a consortium could be formed to the satisfaction of both industry and government, broad service goals and a scenario for such a consortium over the next 50 years might comprise the following:

Phase I: Initial Lunar Outpost.

$He-3$ experimental mining to provide materials to the Outpost and support fusion experiments on Earth - A 5-MW Satellite Power System Prototype for solar electric propulsion and for energy supply to the initial Lunar Base from one of the libration points. NASA would enter into a services contract with the consortium for use of the plant(s), as well as participate in the funding of the RDT&E. Technology components for large-scale power systems, such as space-to-earth energy transmission links and fusion reactors, would be developed in this phase.

Phase II: Lunar Base.

Continued supply of utilities to the expanding Lunar Base - Large-scale mining begins leading to the development of a 50-MW power plant either on the moon or at the libration point(s) for laying the "energy base" for substantially expanded Lunar Base operations. The $He-3$ extraction prototype process is developed and tested end-to-end. Prototypes of the key technology components would be tested "in-situ" at the Base. The knowledge base (technology, costs, risks) of each of the three options could be established for large-scale prototype developments.

Phase III: Large-scale Prototype(s).

This phase will see the deployment of one or more of the three energy options at a scale of several Gigawatts to tens of Gigawatts.

Phase IV: Operations for Commercial Use on Earth.

Operations of the first power system and expension of capacity to meet global energy needs - This would be the ultimate goal of the Lunar Enterprise (i.e., the consortium). Important contributions simultaneously made to the supply of energy and material needs in Space for expanded Space exploration and applications.

CONCLUSIONS

The fundamental conclusion of the Task Force is that the Moon must play a role in long-term terrestrial electricity supply matters. The Task Force also believes that early commercial involvement in this task is of paramount importance in achieving this objective and that a meaningful leadership role for industry is potentially possible. But it recognizes that total industry responsibility for projects of this financial magnitude is not initially possible and government involvement through subsidies or other means, such as co-funding or enabling contracts, is vital.

The primary focus for this study, namely the mining of $He-3$ for transportation to Earth, is a potentially viable economic concept but understandably on a long-range schedule and subject to the establishment of specific conditions, including:

- Required space/lunar infrastructure to be put in place with preponderant government financing.
- Involvement of the private sector in defining and developing this infrastructure.
- Development of a private sector/government relationship that will provide for early private sector involvement which, as stated above, would not be possible under traditional financial and commercial considerations.

- Close coordination between NASA and DOE in the development of a commercial fusion reactor to utilize the lunar He-$_3$ fuel.

The Task Force also reviewed the two solar power concepts, SPS and LPS. On the basis of information provided to the Task Force, these concepts likewise could have long-range economic potential as extraterrestrial electric power sources. The Task Force, however, was not in a position to rate the three concepts in terms of potential economic viability. But it did conclude that each concept has both promise and problems.

A great amount of technical information about all three concepts was developed by, and for the Task Force but more remains to be accomplished to assure confidence in the potential technical feasibility of the systems; much more detailed information concerning cost and scheduling must be developed to provide economic input; and commercial schemes must be developed in some detail to achieve realistic private sector involvement. To this end, we would recommend that NASA and DOE expand its work with academia, industry, and the financial community to further develop the technical, economic and commercial parameters that will better identify extraterrestrial energy options.

But of equal importance is the development of a clear understanding on the part of government and industry, at high levels,

of the fundamental Task Force conclusion that we must look beyond Earth for our long-term electricity needs because of potential damaging ecological impacts with continual major dependence on fossil fuels for terrestrial energy needs. This is a revolutionary concept, and is based on a crucial observation regarding long-term environmental consequences of our current energy production options. There must be understanding, agreement and long-term commitment, and the national will to implement the commitment as a matter of national policy. It also is extremely important to realize that the concept of extraterrestrial energy supply is not the responsibility of any single government agency nor will it seriously be considered if there is not a national commitment.

Lastly, we must recognize that other nations, notably Japan, West Germany and Russia, are proceeding with very aggressive programs to investigate and develop space-oriented, energy systems. It will be done. It is just a matter of by whom.

RECOMMENDATION

As stated in the conclusions, there is need for, and economic potential for the use of the Moon's resources in long-term, terrestrial electricity supply matters. The factual case for this finding, however, needs further development. Because of the long-range nature of these extraterrestrial projects, industry is

not currently capable or willing to assume financial responsibility for these undertakings. The Task Force, therefore, recommends that NASA and DOE continue to support studies that will better frame the development of the projects and provide the additional technical, economic and financial information that will be necessary for greater commitments. The Task Force recommends, however, that these studies not be contracted for under normal government procedures but rather that industry, the financial community, and academia be given a primary role in planning the overall program. This could be accomplished through the establishment of a high-level private sector advisory committee.

The Task Force also recommends that a Workshop be held in accordance with its conclusion that national policy on extra-terrestrial energy supply concepts must be developed. The purpose of the Workshop would be to expose the issue of long-term energy supply options to high-level decision makers, provide understanding about the issue, and seek policy direction and commitment. To be successful, the participants must include high-level representatives of the Administration, appropriate government agencies such as DOE, EPA and NASA, the energy, environment and space leadership of the Congress, electric utilities, the space and energy supply industries, and the financial community. Of equal importance, is detailed planning for

the Workshop. The Task Force recommends that the suggested private sector advisory committee's participation in the planning aspects would be essential.

Concept Description
HELIUM-3 FROM THE MOON

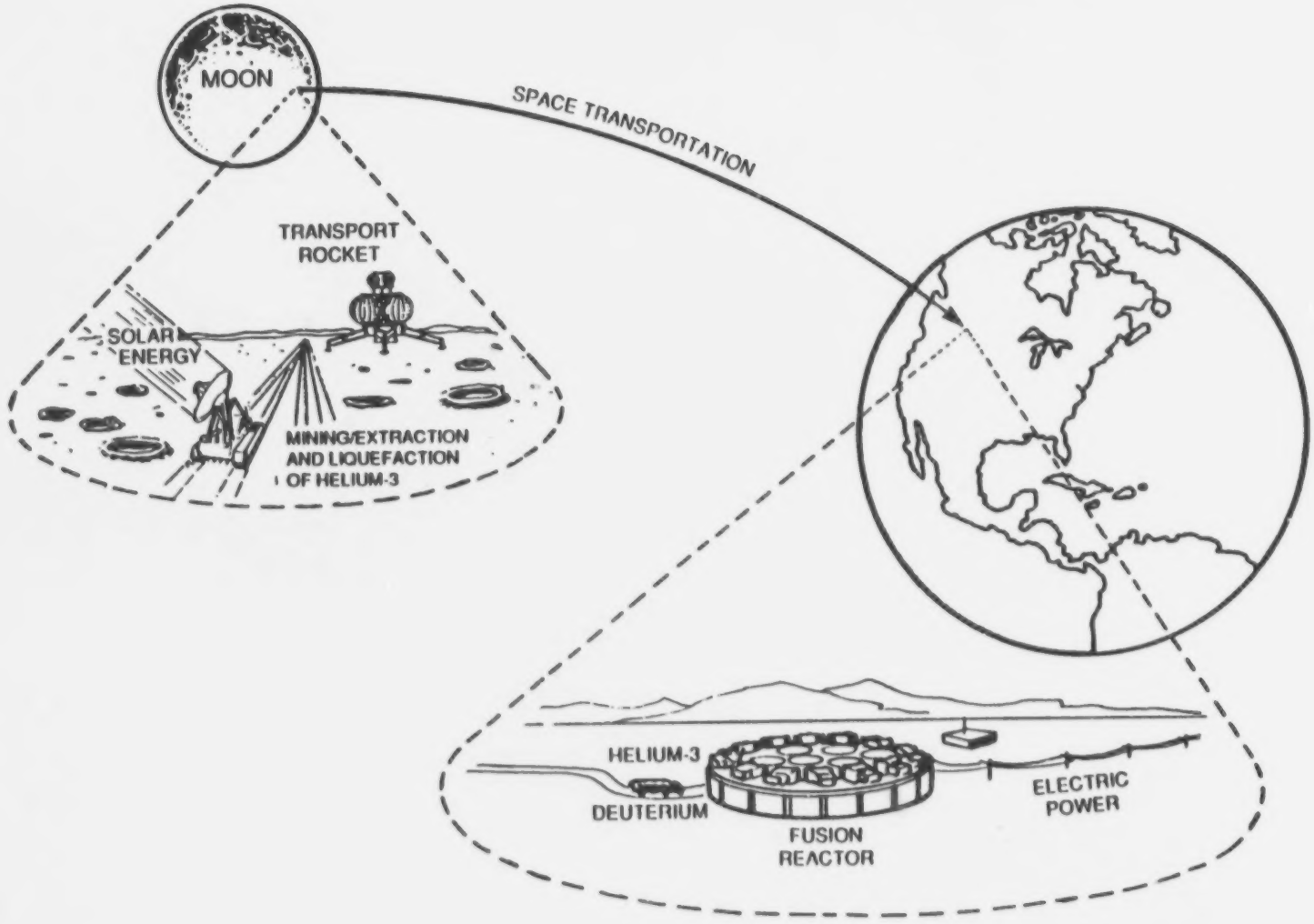


FIGURE 1

Concept Description
SOLAR POWER SATELLITES

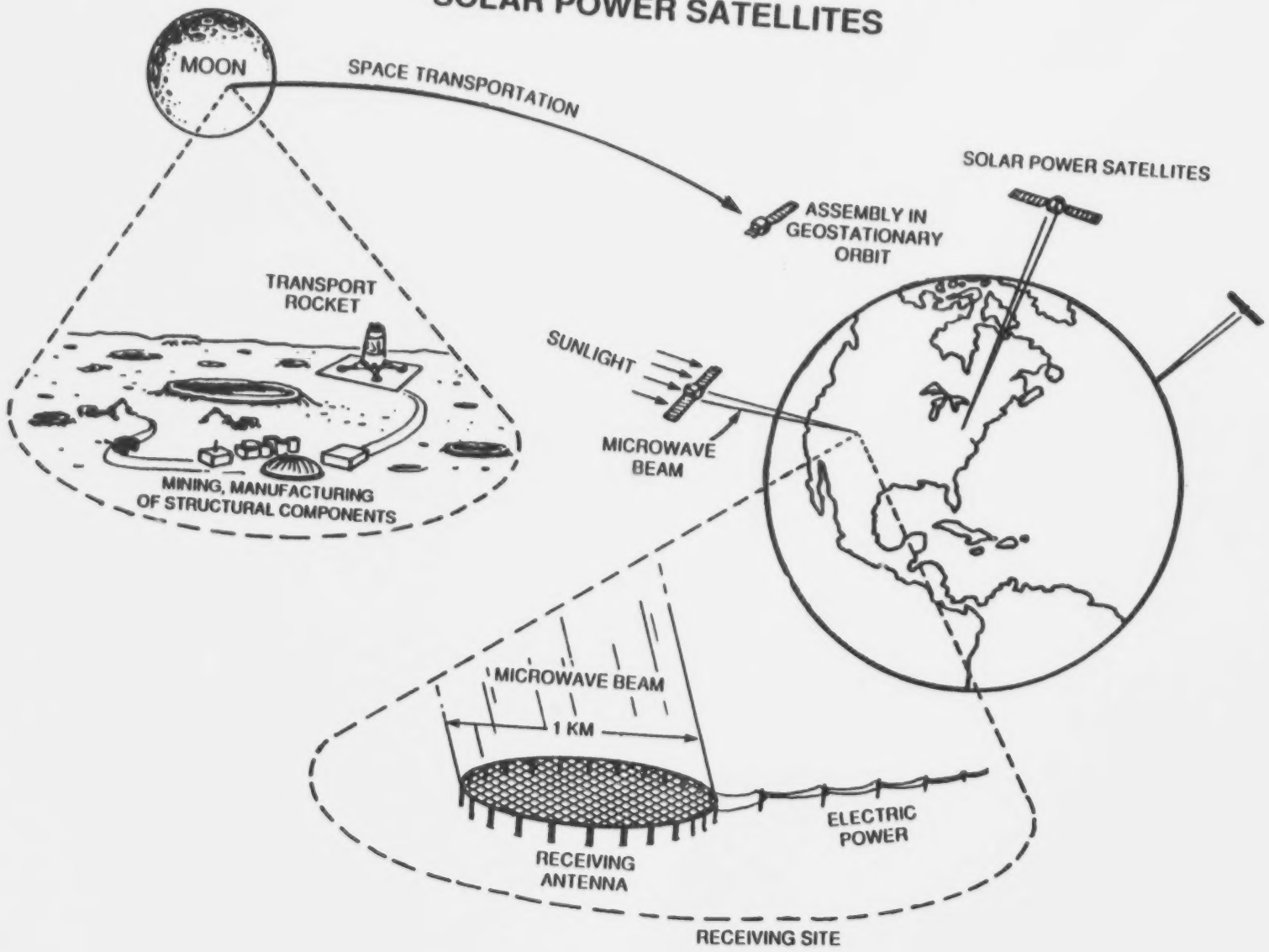


FIGURE 2

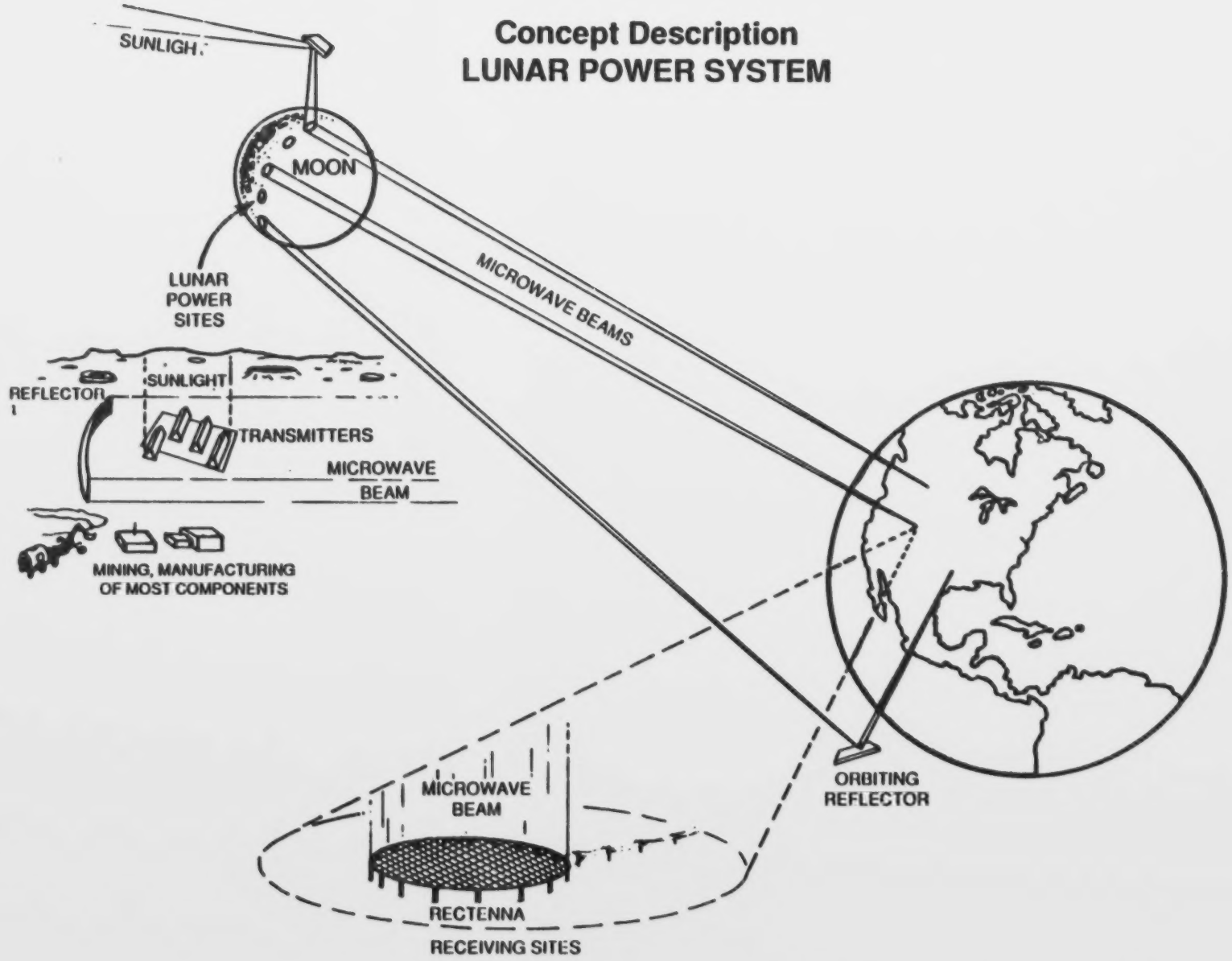

Concept Description
LUNAR POWER SYSTEM
SUNLIGHT
MOON
LUNAR POWER SITES
MICROWAVE BEAMS
REFLECTOR
SUNLIGHT
TRANSMITTERS
MICROWAVE BEAM
MINING, MANUFACTURING OF MOST COMPONENTS
ORBITING REFLECTOR
MICROWAVE BEAM
RECTENNA
RECEIVING SITES

FIGURE 3

APPENDIX A

Membership Listing of

Lunar Energy Enterprise Case Study Task Force

Chairman:

John J. Kearney, Senior Vice President (Retired)
Edison Electric Institute

Members:

George V. Butler, Executive Director
Space Station Division
McDonnell Douglas Aeronautics

W. David Carrier, III
Bromwell & Carrier, Inc.

Dr. David Criswell
University of California, San Diego

Dr. Michael B. Duke, Chief
Solar System Exploration Division
National Aeronautics and Space Administration

Dr. Harold K. Forsen, Senior Vice President & Manager
Research & Development
Bechtel National, Inc.

Dr. Peter Glaser, Vice President
Arthur D. Little, Inc.

John R. Healy, Manager
Generating Schedule/Cost
Potomac Electric Power Company

Dr. Klaus Heiss
ECON, Inc.

Mr. Leonard Hyman, First Vice President
Merrill Lynch Capital Markets Group

Dr. Robert Iotti, Vice President
Advanced Technology
EBASCO Services, Inc.

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Members: (Continued)

Dr. Gerald L. Kulcinski
Department of Nuclear Energy
University of Wisconsin

Dr. B. Grant Logan, Deputy Associate Director
University of California
Lawrence Livermore National Laboratory

Dr. Harrison H. Schmitt, Private Consultant
Albuquerque, New Mexico

Jerome Simonoff
Citicorp.

Dr. George C. Vlases
Department of Nuclear Engineering
University of Washington
And Consultant, Spectra Technology, Inc.

Gordon R. Woodcock
Boeing Aerospace

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APPENDIX B-1

Analysis of the Financial Factors Governing the Profitability of Lunar Helium-3

by

G.L.Kulcinski, H. Thompson, S. Ott
University of Wisconsin

INTRODUCTION

The need for new energy sources in the 21st Century has been established in the body of this report and the benefits of using the DHe3 fuel cycle are discussed in Appendix B2. Assuming that such an energy source can be brought on line by the year 2015, this appendix will address the following questions;

A.) What are the financial factors which can have the greatest leverage on the profitability of DHe3?

B.) Over what range can these financial factors be varied to keep the DHe3 option profitable?

C.) What ultimate effect could this energy source have on the price of electricity to US consumers?

We will not address the environmental features of this fuel cycle nor the procurement of the He3 fuel from the Moon as both of these topics have been covered elsewhere (1-6). Our sole purpose here is to concentrate on the financial aspects of this fuel.

1.) L. J. Wittenberg, J. F. Santarius, G. L. Kulcinski,"Lunar Source of He3 for Commercial Fusion Power", **Fusion Techn.** ,10, 167 (1986)
2.) G.L.Kulcinski, and H. H. Schmitt, " The Moon: An Abundant Source of Clean and Safe Fusion Fuel for the 21st Century", Published in the Proc. of the 11th Intern. Sci. Forum on Fueling the 21st Century, Sept. 6, 1987, Moscow, USSR
3.) G.L. Kulcinski, et. al., "The Commercial Potential of D-He3 Fusion Reactors", Proc. 12th Symp. on Fusion Engr., IEEE Cat. No. 87CH2507-2, 1987
4.) G.L. Kulcinski et. al., " Apollo- An Advanced Fuel Fusion Reactor for the 21st Century," **Fusion Techn.**, 15, 1233(1989)
5.) J.P. Holdren et. al., "Exploring the Competitive Potential of Magnetic Fusion Energy" **Fusion Techn.**, 13,7 (1989)
6.) I. N. Sviatoslavsky and M.Jacobs, " Mobile He3 Mining and Extraction System and its Benefits Toward Lunar Base Self-Sufficiency", To be Published.

Assumptions and Approach

The main assumptions made for this study are listed in the accompanying table. The acceptance that DHe3 plasmas can be effectively utilized to provide electricity on the Earth with sufficient environmental advantages so as to be aggressively pursued by the developed nations is taken as an initial starting point. It was also assumed that there is no question about the magnitude and distribution of He3 on the surface.

The basic figure of merit used here is the real rate of return on investment. The analysis has been confined to the U.S. only and covers the period from 1985-2050. All the calculations have been in 1988 dollars, i.e., inflation has not been included.

The results have been viewed from 3 different perspectives;

- From that of an electric utility which is interested in providing a reliable form of safe, clean, and economic electricity and views He3 as a fuel only,
- From that of a lunar developer whose main goal is to mine and sell a product (He3) at an attractive profit,
- From that of a vertically integrated energy company which owns both the 'mines' and the power plant.

Real Rate of Return Investment Method

Two complementary methods of analysis are used to assess the benefits of using lunar He3 in the DHe3 fuel cycle to provide some of the electricity needed in the United States for the first half of the 21st century. They are;

1.) Rate of return on incremental investment required,
and 2.) Reduction revenue requirements (total cost to customers) achieved.

The first step in this type of calculation is to establish the future electrical demand(see accompanying diagram). Next, two scenarios to satisfy this demand are constructed. The first relies simply on coal and fission (it is assumed that in the 21st century oil and natural gas will not be used to any great extent to produce electricity in the U.S. and the contribution from hydro plants is ignored at this time for simplicity). The second scenario assumes that DHe3 fusion will start to contribute in the year 2015 will a penetration rate described in more detail later.

Once the amount of kWh's produced by each form of energy is calculated, the incremental investment and cash flows for each scenario can be determined. The difference in total cash flow between the two scenarios is then the incremental investment required. In method 1, it is the rate of return on the incremental investment that captures our interest. This rate of return measures the benefit to society from the increased capital

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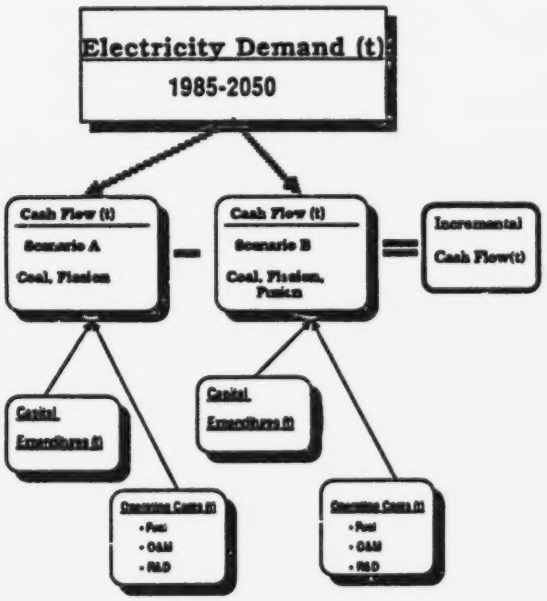
investment in the fusion alternative.

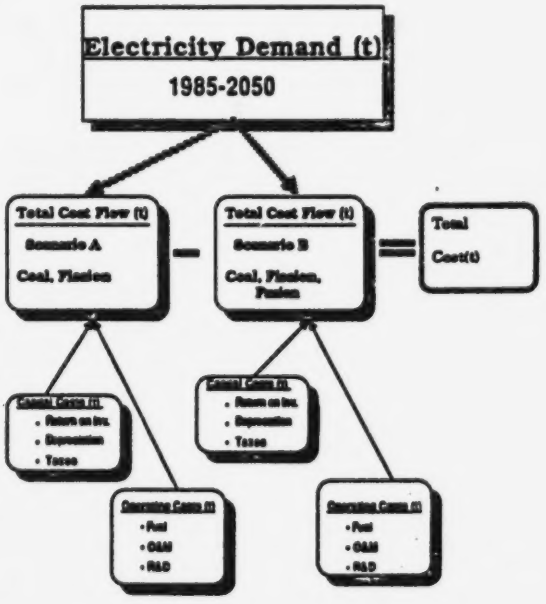
The calculation of the kWhr's produced by each form of energy can also be used to calculate the reduction in revenue required achieved through the use of DHe3. (Method 2). The revenue requirements (total annual costs of generating electricity)--which the ultimate consumer must bear-- consist of the costs of capital, taxes and the costs of operation. By adding the yearly costs of each, the total cost per kWh for each of the two alternatives can be calculated. The calculations are made using the same procedures used in rate cases for regulated utilities. The revenue requirement, or total cost, is the sum of depreciation, fuel costs, O&M costs, R&D costs, taxes, and return on investment.

The main financial assumptions, which are relevant only to method 2, are: (1) the financing mix consists of 50% debt and 50% equity; (2) the cost of debt is 10% and the cost of equity is 13%; (3) the effective corporate income tax is 30%. These assumptions, along with others on the parameters governing costs allow calculation of the rates(mills/kWh) consumers would be charged. This another way to measure the benefits to society.

It is important to note that both methods understate the RRR because we have arbitrarily cut off the calculation at the year 2050 even though much of the equipment and power plants still would produce electricity in the future.



Method 1
Rate of Return on Incremental Investment



Method 2
Total Cost Reduction

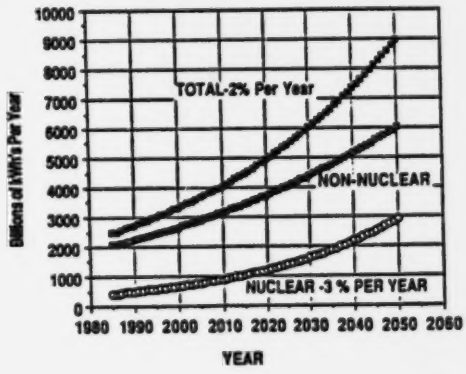
Projected Electricity Demand 1985-2050

It has been assumed that the U.S. growth rate in electricity demand over this period is 2% per year. While no one can really predict this number with any accuracy, it is less than 1/2 the growth rate of the 1970's and considerably lower than the current growth rate from 1985-1988 (3.2%). Most of the DOE and electric utility predictions fall in the 2 to 3% range and a recent Edison Electric Institute report concludes that the growth rate will be in the 2% range from now to 2020.

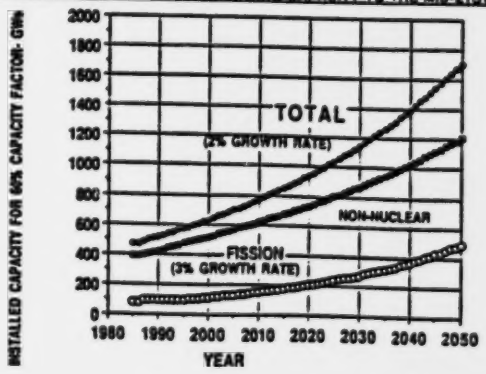
The result of a 2% annual increase in electrical demand is illustrated in the accompanying graphs, both for installed capacity and for the total kWh's generated. For the purposes of this study we have assumed that nuclear power grows at 3% per year after 1995 and that the difference between the 2% overall growth and the 3% nuclear growth (albeit on a smaller base) is made up by coal. This scenario envisions that the electrical energy consumed in the U.S. will rise from 2.5 trillion kWh's in 1985 to ≈ 9 trillion kWh's in 2050. Approximately 1/3 of that energy in the year 2050 would be provided by nuclear power.

The total installed capacity also rises from ≈ 500 GWe in 1990 (calculated on the basis of an average 60% capacity factor) to ≈1700 GWe in the year 2050. The installed nuclear capacity grows from ≈100 GWe in the mid 90's to ≈500 GWe by the year 2050.

Projected U.S. Electrical Power Generation



PROJECTED ELECTRICAL GENERATING CAPACITY TO THE MID-21ST CENTURY



Calculation of Electrical Generation Costs Without Fusion

The total cost for generating electricity in this case is the sum of coal and fission produced energy. Given the demand scenarios previously described, there are three main factors to consider; capital costs, fuel costs, and O&M costs. In addition, the true cost of the electricity should include the R&D required to keep the plants running competitively. All of these factors must be included in the total busbar cost(see accompanying flow diagram).

The current capital costs for coal plants in this study were assumed to be 1400 $/kWe and the corresponding value for fission plants is 2650 $/kWe. Both of these numbers come from recent DOE summaries of existing plants. It is recognized that some new facilities cost more and some cost less, but these averages seem to reasonable at this time.

Current fuel costs for coal plants average 33.13 $/ton which translates into 19 mills/kWh. Similarly, current fission reactor fuel costs are about 7 mills/kWh. The lower fission fuel costs are countered somewhat by its higher O&M costs. Presently fission O&M costs average 10 mills/kWh versus 4 for coal. In order to reflect environmental factors, we have allowed the fuel and O&M costs to escalate by 2 % per year. These environmental costs include mine and plant clean up, increased emission costs and increased waste management costs.

The current R&D costs are taken to be those funded by the Federal Government through DOE. These currently run 800 $M/y for both technologies and because of the concern over the environment, we have allowed 4% escalation in these costs.

Calculation of Electrical Generation Costs With Fusion

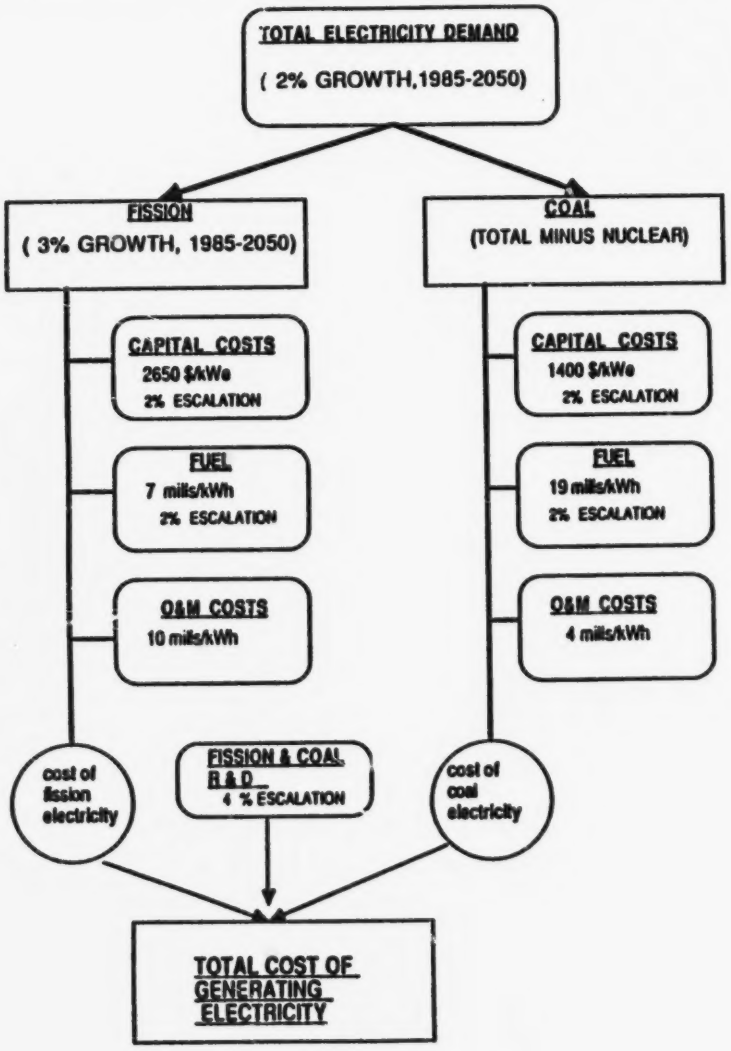
This calculational procedure is identical to that without fusion. The capital cost for a DHe3 fusion reactor was taken from the Apollo reactor study at the University of Wisconsin. The 1200 MWe facility was costed out at 2030 $/kWe and the O&M costs amounted to 5 mills/kWh. The fuel cost is the cost of operating the moon base including the transportation costs of materials taken to the moon and the cost of returning the fuel.

The current magnetic fusion R&D costs are ~350 $M/y and it was assumed that these costs escalate at 4 %/y exclusive of inflation.

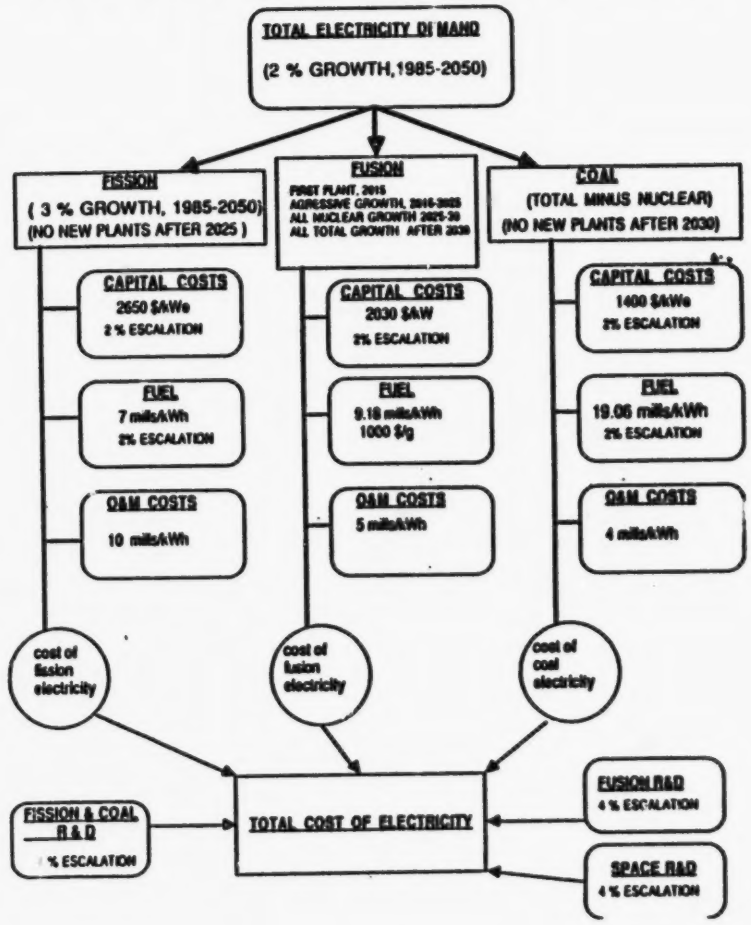
Finally, the R&D needed for Space research must be included. We only included R&D specific to He3 and assumed that heavy lift vehicles, a scientific base on the Moon as well as the basic research needed to return to the Moon for scientific reasons would be part of the national program. The specific He3 Space related research was assumed to start in 1991 at a 10 $M/y level, rapidly escalating to a 100 $M/y by the mid 1990's and thereafter growing at a real rate of 4%/y.

The rate of return analysis which follows will consider a return to the lunar company as well as to the utilities. This is accomplished by assuming a selling price for He3 from the Moon. The base case cost is 1000 $/g. This translates into a fuel cost of 9.18 mills/kWh. Varying this transfer price will merely shift profits between the lunar company and the utilities without affecting the return to society as a whole.

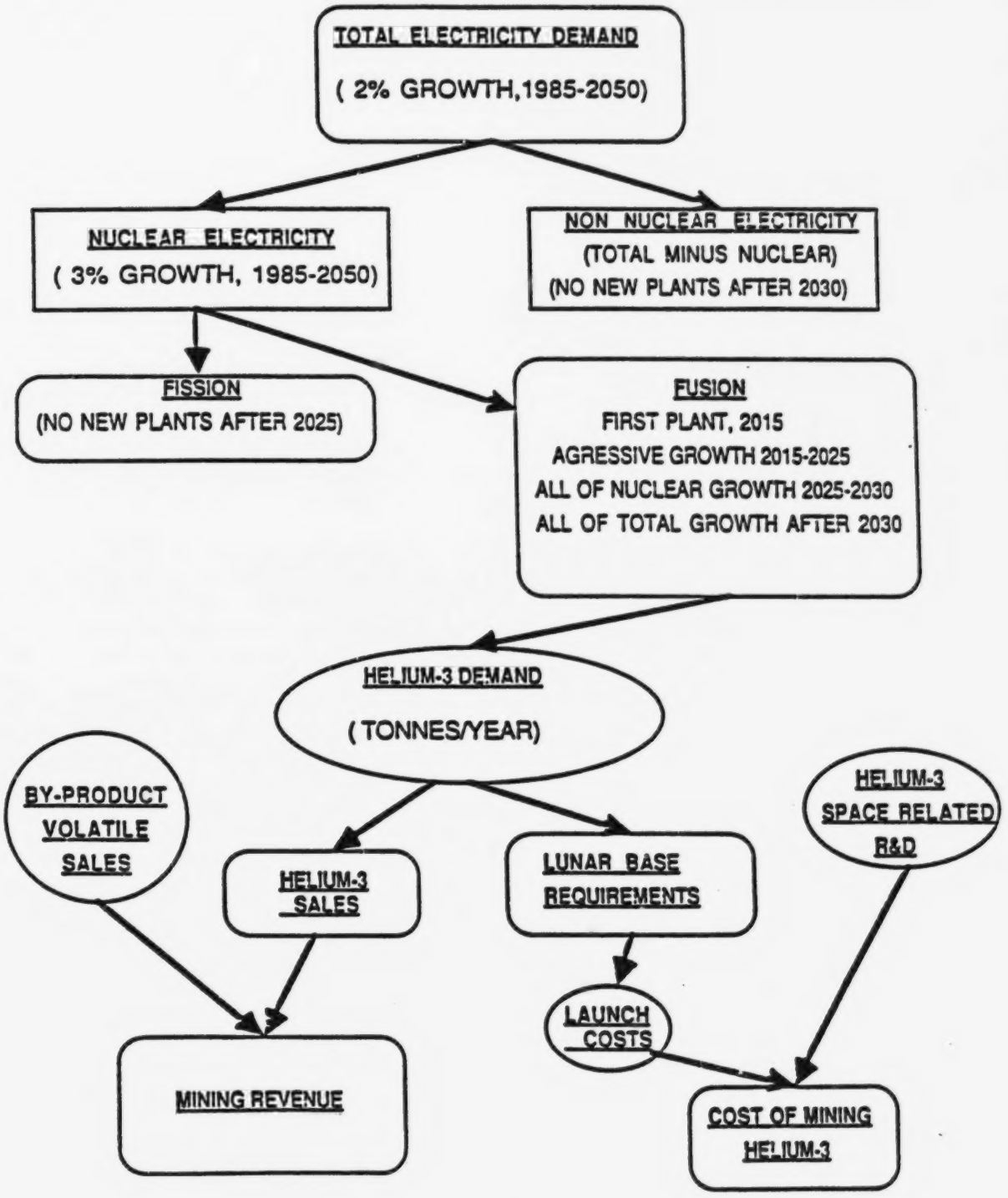
REFERENCE COST FOR ELECTRICITY GENERATION, 1985-2050



EFFECT OF DHe3 FUSION ON THE REFERENCE COST FOR ELECTRICITY GENERATION, 1985-2050



CALCULATION OF PROFITABILITY OF LUNAR He3 MINING

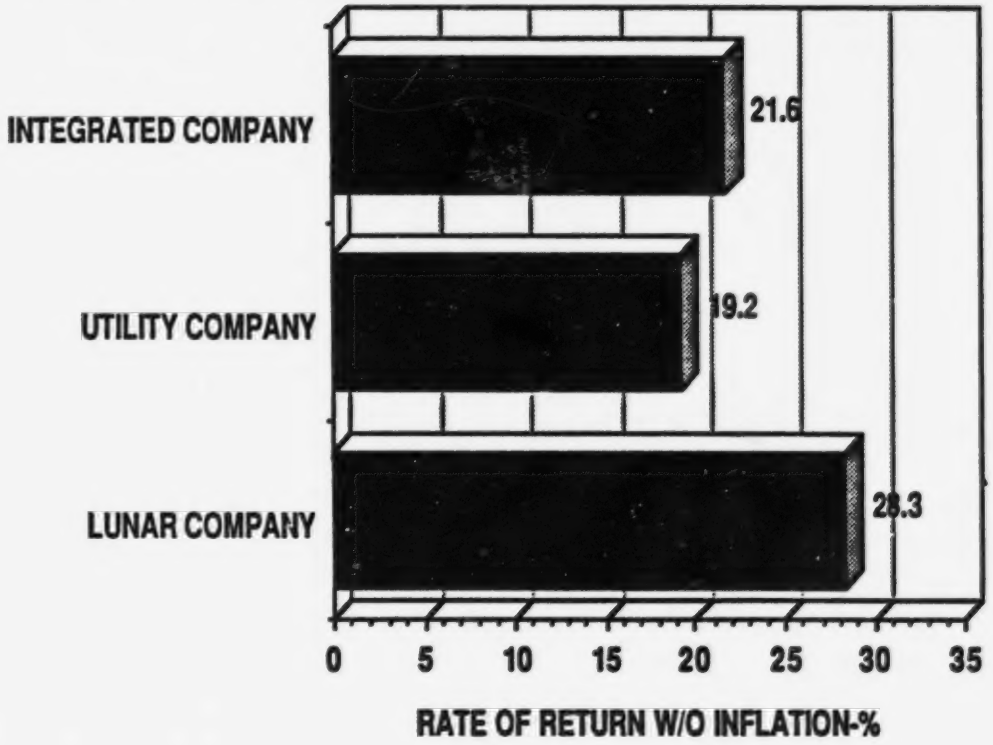


Base Case Profitability For DHe3 Fusion

Using the energy demand scenarios described earlier, along with the input information on coal, fission, fusion, space, and R&D cost, we have calculated the internal rate of return on the incremental investment in fusion. The accompanying graph shows that if the selling price of He3 is $1000/g, the Lunar Company could realize (before including inflation) a 28.3 % rate of return. The Utility Company could still obtain a 19.2% profit and if the Lunar and Utility Companies were owned by the same organization, the rate of return would be 21.6%. Obviously the 'financial center of gravity' is close to the Utility company.

The effect of inflation on the base case was examined next. It was found that if the inflation rates were on the order of 4%, the rate of return then approached ≈ 25% for both the Earth and Lunar based companies(see the accompanying graph).

PROFITABILITY OF He3 FUSION ENERGY IN THE 21ST CENTURY-BASE CASE



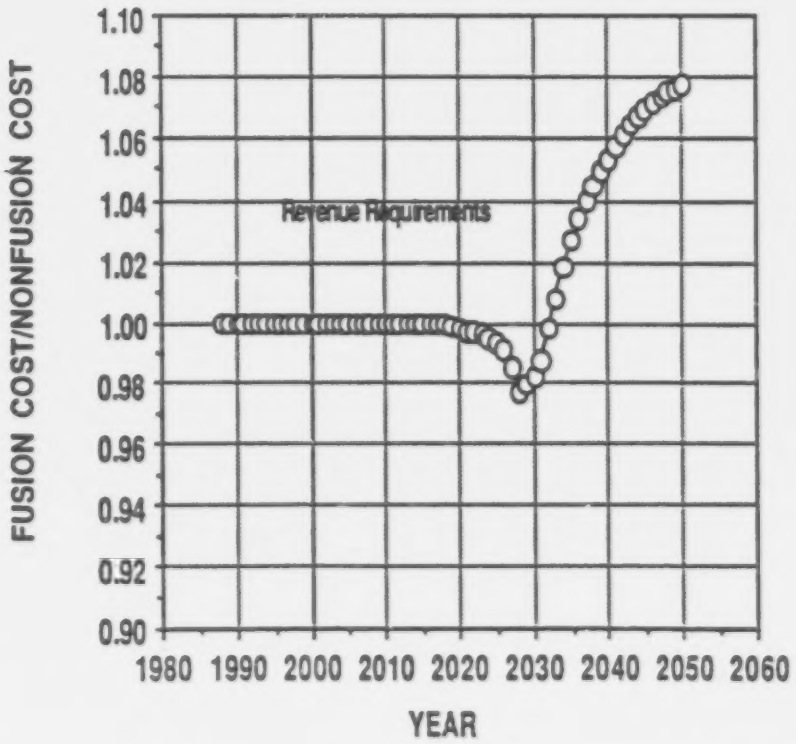
Annual Capital Cost Comparison

In order to develop a complete financial picture, we need to calculate the total cost of electricity to the consumer. Input to that calculation includes the capital costs and the operating costs, each of which we will calculate separately, then combine them into a final cost of electricity comparison. The analysis of this data is for the Vertically Integrated Company and includes all the costs to the ultimate customer and thus serves as a measure of the effect on society.

The annual capital costs plus taxes includes depreciation charges resulting from an assumed plant life of 40 years, return on investment, and income taxes. For each alternative it is assumed that capital requirements will be financed with 50% debt and 50% equity capital. The cost of equity is assumed to be 13% and the cost of debt is 10% for each alternative. Profits are assumed to be subject to a 30% income tax rate.

The ratio of the capital cost required for the two scenarios is plotted in the accompanying diagram for the Integrated Energy Company. From the year 2015 to ~2025, the capital requirements are slightly less for the fusion case. After 2025, when fusion begins to replace large amounts of more expensive fission power , the ratio drops to 97% of the nonfusion case. However, when fusion begins to replace the less expensive coal plants after 2030, the ratio climbs to 108% of the base case.

ANNUAL CAPITAL COST COMPARISON

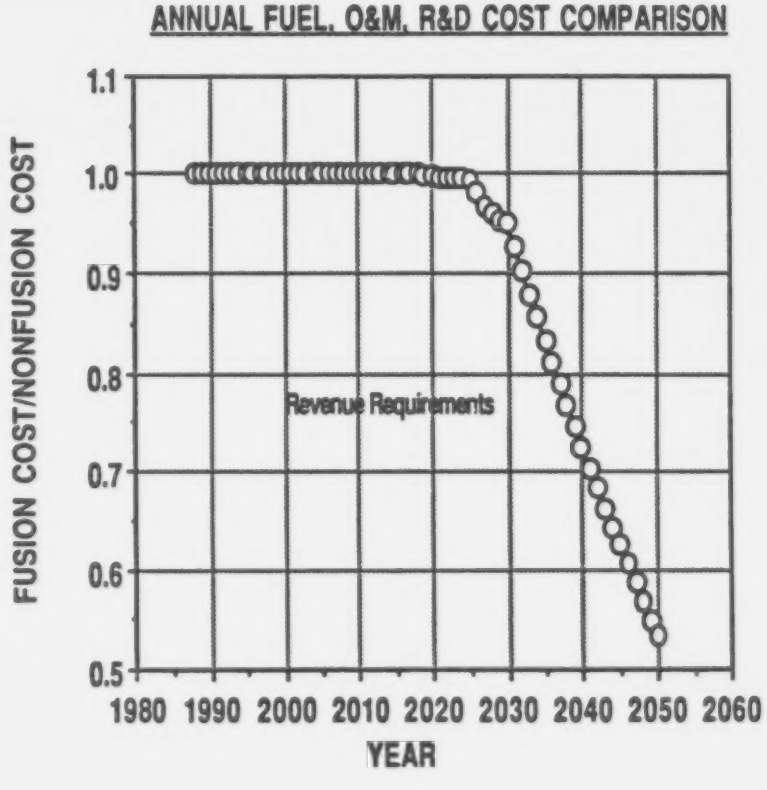


Annual Operating Cost Comparison

The analysis of lunar base costs suggests that there will be economies of scale present in the mining of He3. It is also obvious that the amount of He3 required in the fusion alternative will increase dramatically between the first installation of a fusion plant in 2015 and the 'cnd point' of the analysis in 2050. This increasing economy associated with He3 mining will cause the fuel costs for the fusion alternative to decline significantly towards the middle of the 21st century.

Non fusion fuel costs include escalation factors for fission and coal costs to represent the diseconomies associated with environmental and economic limitations of these methods of production.

The ratio of the operating cost required for the two scenarios is plotted in the accompanying diagram for the Integrated Energy Company. From the year 2015 to ~2025, the operating cost requirements are slightly more for the fusion case because of the added R&D costs. After 2025, when fusion begins to replace large amounts of the more expensive fission operating costs , the ratio drops to 95% of the nonfusion case. However, when fusion begins to replace the much more expensive coal plant operating costs after 2030, the ratio drops rapidly to only ~50% of the base case by 2050.

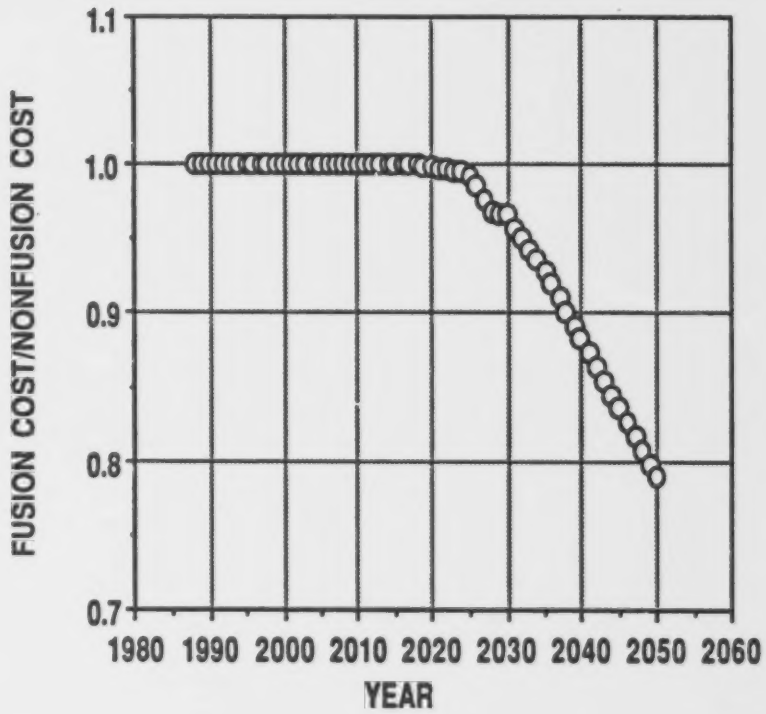


Effect of DHe3 Fusion on the Consumer Cost of Electricity

The previous two graphs are combined to calculate the effect of DHe3 on the costs which consumers pay for electricity.

The ratio of the cost per kWh from the fusion alternative to that from the nonfusion alternative is shown on the accompanying graph. The cost per kWh for the fusion case is slightly (1%) higher in the early years because of the added R&D for fusion and space. However, by the year 2020 the two costs are equal again and by 2025 the ratio starts to move rapidly in favor of the fusion case. By the year 2050 the composite cost of electricity has fallen to 80% of the nonfusion case.

RATIO OF ELECTRICITY COST, MILLS/kWh, FOR FUSION AND NONFUSION SCENARIOS



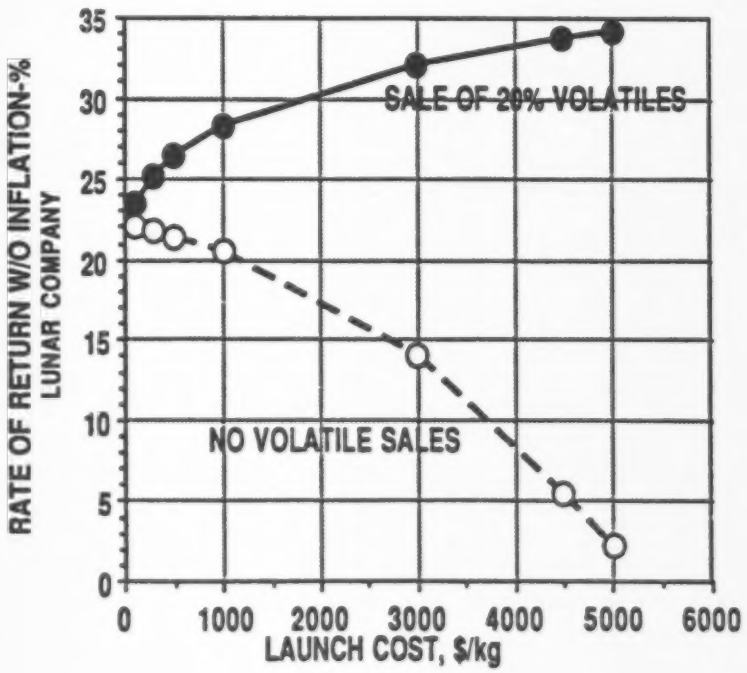
The Dependence of Helium-3 Profitability on the Cost of Launching Payloads to the Moon

One of the major costs for procuring Helium-3 is the cost of carrying the equipment and lunar base facilities to the Moon. This cost depends on both the amount of material needed from the Earth and the cost per kg of placing that mass on the Moon. Today it costs ~$4000/kg to place material in low earth orbit (LOE). This number must be multiplied by 4 to 6 to place the same kg on the Moon, making current launch costs equal to ~$15,000 to $25,000/kg. It is the stated goal of the U.S. Space Program to reduce the payload cost to LEO to ~ $250/kg. This would imply that launch costs to the Moon might approach ~$1000/kg of payload. We have chosen $1000/kg for our base case in this study but we have examined variations from $100 to $5000/kg.

A complicating feature of our present scenario is the treatment of the by-products from He3 mining such as water, hydrogen, nitrogen, etc. For this study we have assumed that 20% of the volatile by-products can be "sold", either to the scientific base, to a foreign country lunar base, to the Space Station, or to offset the cost of bringing these same volatiles to the Lunar Company base camp. The volatiles are assumed to be sold at 50% of the launch cost.

A wide variation in launch costs is shown in the lower graph which reveals that even if the launch costs were zero, the rate of return is no larger than ~23% because of the R&D invested in Space Research. On the other hand, if the launch costs approach ~$5000/kg, the Lunar Company becomes unprofitable if no credit is claimed for the excess water, hydrogen, nitrogen, etc. If the volatiles can be sold, then the higher the launch costs, the higher the profitability.

EFFECT OF LAUNCH COSTS ON THE PROFITABILITY OF DHe3 FUSION

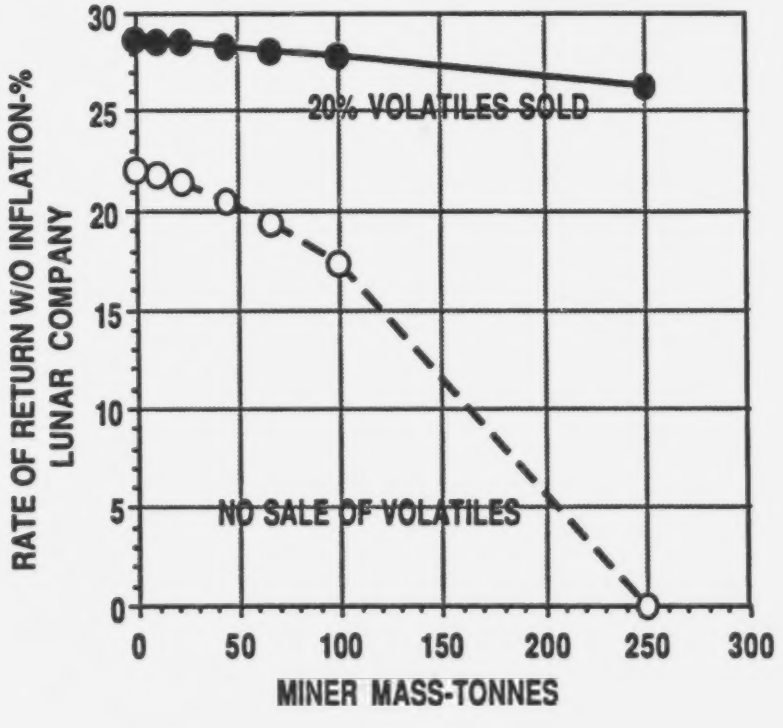


Effect of the Mass Launched to the Moon on the Profitability of DHe3 Fusion

Current designs for the mining of He3, its separation from other lunar volatiles, purification, and condensation show that the mass of one unit that will produce 33 kg of He3 per year is 43.6 tonnes. Furthermore, it is assumed that this equipment will last ≈ 20 years. Also required, along with the mining equipment, are the personnel, living habitat, and consumables for life support. This latter mass amount to 820 kg per person year. We have looked at a 50% variation on the base case launch mass of 43.6 tonne/unit, i.e., 66 and 22 tonnes per unit. The results are shown on the upper graph on the next page.

The results of rather large variations in the mass launched to the Moon show that there is only a small effect on the profitability of the Lunar Mining Company (≈ 1%) and essentially no effect on the overall profitability of the integrated Helium-3 system. In fact, it was found that the miner mass would have to be increased by more than a factor of 5 before the profitability would be threatened(see lower graph on the next page) for the case where no volatiles are sold. If some of the volatiles are sold, then the mining equipment mass can increase a factor of 10 over the base case without serious erosion of the profitability.

EFFECT OF MINER MASS ON PROFITABILITY OF DHe3 FUSION



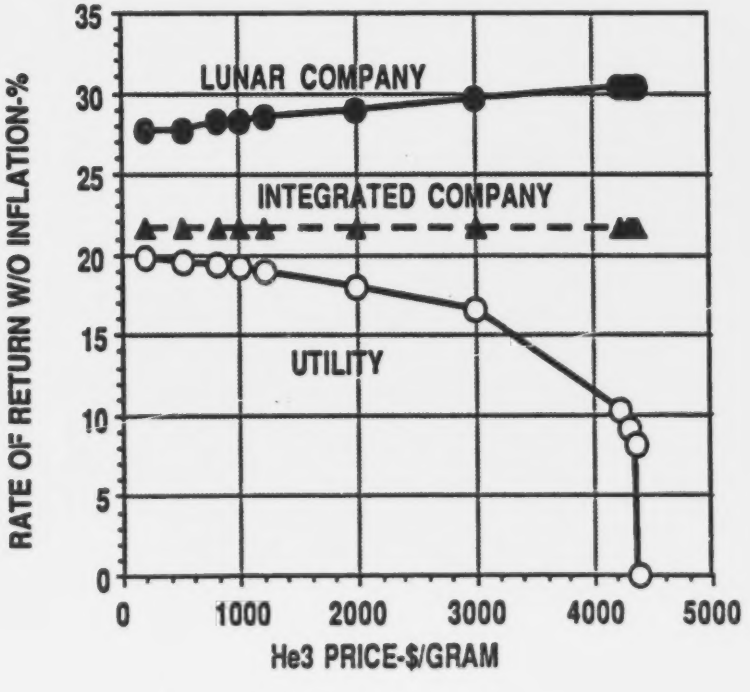
Effect of He3 Price on the Profitability of DHe3 Fusion

One of the most often asked questions in this analysis is "What is the allowable price of He3 to the Utility and the Lunar Mining Company?" Early analyses showed that He3 could cost as much as $1000-$2000/g and still allow DHe3 fusion to be economically competitive. As noted previously, we chose the base case value as $1000/g and tested the sensitivity to variations of plus or minus $200/g. It was found that $200/g variations resulted in less than 1% changes in the profitability of the Lunar Company and <1% in the profitability of the Utility Company. There was no change in the profitability of the Integrated Company since the price of He3 is merely an internal transfer with in the Integrated Company and does not effect the overall profitability

A wider variation in the Helium-3 price is included in the figure below. There are two important observations with respect to our strawman companies. On the low side, it appears that even at a He3 price of $500/gthere is an attractive (~25%) return on investment in the Lunar Company. It is also shown that even if He-3 were free, the profitability of the Utility would not be more than 20 %.

On the high side, it was found that the He3 price needs to be below $4000/g to insure a 10% return on the Utility Company. At a price of $3000/g, the profitability of the Lunar Company will exceed 30%. The profitability of the Integrated Company is unaffected by the He3 price because it balances the profits of one company against the losses of another company.

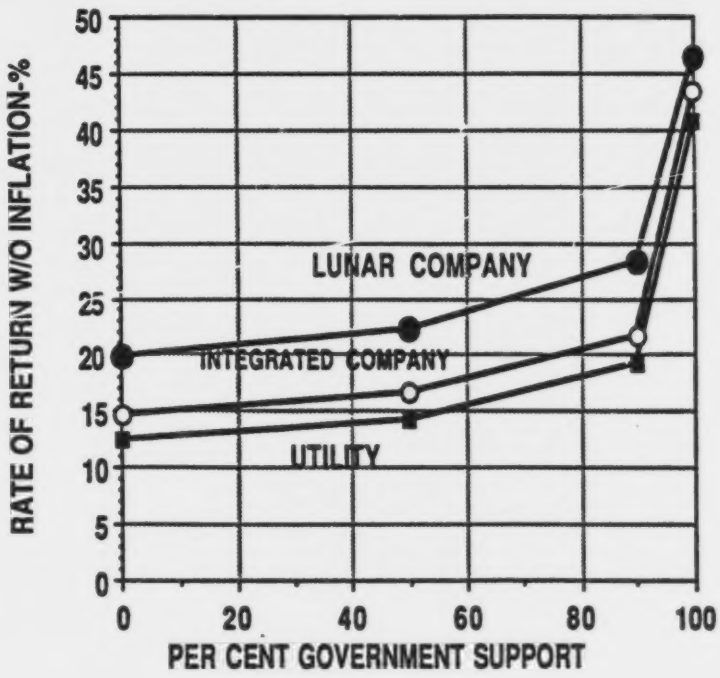
EFFECT OF HELIUM-3 PRICE ON THE PROFITABILITY OF DHe3 FUSION



Effect of Source of R&D Funding on the Profitability of DHe3 Fusion

The question of who provides the funds for needed coal, fission, fusion, and space R&D is important to the overall profitability of this analysis. The possibilities range from 100% governmental support to 100% private funding. This range is explored in the graph on the next page and it reveals that if all the R&D is funded by the government, the profitability soars to values of 40% or more. However,even if the R&D is supported solely by private industry, a very respectable rate of return of ~15% is calculated. Perhaps a more likely case is for a 90-10 split between government and private industry. Under these circumstances, the profitability is in the 20-25% range.

EFFECT OF GOVERNMENT SUPPORT ON THE PROFITABILITY OF DHe3 FUSION



Conclusions

It is convenient to address the conclusions from this work with respect to each of the companies considered.

Utilities

- The Real Rate of Return (RRR) is quite attractive (i.e., >19%) for the base case even without escalation for inflation.
- For a given He3 price, the RRR is not very sensitive to ± 10 % variations in capital or non-fuel O&M costs for fission, fusion, or coal systems.
- The RRR is moderately sensitive to present fuel costs for coal and fission systems as well as to future escalation in those costs.
- The RRR is not as attractive for fusion if fission and/or coal capital costs are equal to or less than inflation.
- The RRR is quite sensitive to the level of government R&D support for fusion in the next 10-15 years.

Lunar Mining Company

- The Real Rate of Return (RRR) is extremely attractive (i.e.,>28%) for the base case even without escalation for inflation.
- If the volatile by-products are not considered as a revenue source, then the RRR is very sensitive to;

  Launch Costs (Should be < 3000 $/kg)
  Launch Mass (Should be < 150 tonnes /miner)
  He3 Selling Price (Should > 500$/g)

  The sale of even a small fraction of the volatiles (≈ 20%) removes the above restrictions and allows for a very profitable operation even at high launch costs, high miner masses, and low He3 prices.
- The RRR is sensitive to whether the Space R&D over the next 10-15 years is supported by the Federal Government or by Private Industry.

Integrated Energy Company (IEC)

- The Real Rate of Return (RRR) is quite attractive (i.e., > 21%) even without escalation for inflation.
- The RRR for the IEC is insensitive to the price and cost of He3 (at least within the scope of this study.
- The RRR is quit sensitive to the escalation in the capital costs and fuel prices of non-fusion energy sources.
- The RRR is quite sensitive to whether the space R&D is financed by the Federal government or by private sources.
- The revenue from the sale of even a small (≈20 %) amount of the lunar volatiles can be very beneficial to the profitability of the IEC

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INTRODUCTION TO D-^{3}He FUSION REACTORS

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Spectra Technology, Inc.

I. INTRODUCTION

Research on producing controlled thermonuclear fusion reactors, with the goal of developing commercial central-station power plants, has been pursued around the world since the late 1950's. Most of the effort during these four decades has been devoted to harnessing the deuterium-tritium fusion reaction,

$$_1^2D + _1^3T \rightarrow _2^4He + _0^1n,$$

in which the α particle ($_2^4He$) has an energy of 3.5 MeV and the neutron has an energy of 14.1 MeV. This reaction has been emphasized because it has the largest cross-section under laboratory conditions, and because both D and T (bred from Li) are readily available.

Another fusion reaction, namely

$$_1^2D + _2^3He \rightarrow _2^4He + _1^1p \rightarrow 18.4\ MeV$$

has long been recognized as offering certain significant advantages over the D-T reaction, which arise mainly from the fact that no neutrons are produced. Nevertheless, D^3-He plasmas have not been experimentally investigated to any great degree due to the scarcity of terrestrial ^{3}He. The recent discovery of significant amounts of ^{3}He in the lunar regolith, however, has prompted a critical re-examination of the advantages and disadvantages, relative to "conventional" D-T fusion, which would accrue from the use of the D-^{3}He cycle. This work was initiated and has been pioneered by the Fusion Technology group at the University of Wisconsin, which was the first to recognize the importance of the lunar ^{3}He resource

for terrestrial fusion.[1] Other groups, including the Lawrence Livermore Laboratory, the University of Illinois, Spectra Technology, Inc. and the Institute of Plasma Physics at Nagoya University, have begun studies in this area. The purpose of this appendix is to summarise the findings of these studies. An earlier account of the work can be found in the Proceedings of the Lunar ^{3}He Fusion Power Workshop[2] in which the fusion power working group concluded: "There appear to be significant potential advantages to a D-^{3}He fueled fusion reactor. These advantages could become compelling with respect to environmental[A safety, licensing, and public acceptability."

II. FUSION REACTORS

A simplified schematic cross-section of a conventional D-T based magnetic fusion reactor is shown in Fig. 1. The plasma or fusion fuel, which consists of electrically-charged particles, is confined in a vacuum chamber, away from the walls, by magnetic fields created by superconducting magnets. The plasma core is surrounded by a "first wall" which absorbs most of the radiant heat load and some of the plasma particle energy, a blanket which absorbs the neutron energy and breeds tritium, a shield to protect the magnets and prevent all radiation leakage to the outside, and finally, by the magnets. The heat produced in the first wall structure and blanket is used to power a thermal cycle and generate electricity by conventional means.

In addition to the "toroidal" confinement device typified by the Tokamak shown in Fig. 1, there exists a class of cylindrical or simply connected confinement configurations, including tandem mirrors, FRC's and spheromaks, which have certain potential advantages and disadvantages relative to Tokamaks; these are discussed briefly later in this report.

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1. L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, Fusion Techn. 10 167 (1986).

2. Proceedings of the Lunar ^{3}He Fusion Power Workshop, April, 1988, Cleveland.

Fusion plasma physics research has been directed at achieving a level of understanding of plasma confinement and heating which would lead to the attainment of parameters necessary to create a sustained, controlled fusion reaction. The intermediate goal is to demonstrate this in devices of the appropriate scale to ultimately be developable into commerically-competitive power plants. Most of the effort has been concentrated on Tokamaks, which have achieved the required temperatures, and are within a factor of three of the required "confinement parameter" $n_i\tau_e \sim 2 \times 10^{20}$ ions-seconds/m^3, where n_i is the ion density and τ_e the energy confinement time. The other magnetic fusion confinement concepts mentioned above have received far less study and are not as advanced, although progress is very rapid with some of them.

In the past two decades, fusion research has expanded beyond plasma physics to include a major effort in technology, including reactor system studies and component development. Key materials problems have been identified, which arise principally from the energetic (14.1 MeV neutrons) produced in the D-T reaction. These lead to degradation of material properties, particularly at high temperatures, which will probably necessitate replacing the first wall and inner blanket of a D-T based reactor every three to five years. In addition, induced radioactivity associated with these energetic neutrons leads to moderate afterheat and waste disposal problems, although they are significantly less severe than for fission systems.[3]

III. GENERIC ADVANTAGES AND DISADVANTAGES OF THE D-^{3}He FUSION CYCLE

A summary chart of the relative merits of D-T and D-^{3}He cycles is shown in Table 1. As mentioned in the introduction, the principal reaction, D + ^{3}He $\rightarrow$ ^{4}He + p, produces no neutrons. All of the energy is produced in the form of charged particles. Some of the energetic charged particles escape from the confined plasma volume fairly quickly and can be used for direct energy conversion, leading to higher efficiency and reduced waste heat. The

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3. "The ESECOM Committee Executive Summary," J. Holdren et. al., Fusion Techn. 13 7 (Jan. 1989).

balance of the energy released serves to heat the plasma; in steady state this heating is balanced by radiation, convection, and conduction losses. The relative magnitudes of these loss mechanisms depends on the confinement scheme.

Although the primary D-^{3}He reaction produces no neutrons, a few are produced from side reactions involving D-D and D-T fusions. The fraction of total energy produced in neutrons, however, is typically four percent at T_e = 50 keV for a 50:50 D-^{3}He mixture, and can be made much lower (<1%) by reducing the D concentration or increasing T_e, at some cost in fusion power density. When this is compared with the 80% fraction of fusion energy in neutrons for a pure D-T cycle, the enormous technological advantage of D-^{3}He becomes apparent.

The relative absence of neutrons has several advantages. First, the radiation damage is drastically reduced, and reactors can be designed whose components should survive the entire lifetime of the reactor[4] based upon state-of-the-art materials. This should result in decreased maintenance and increased capacity factor, which favorably impacts the economics. Secondly, the reduced activation makes possible passively safe reactor designs, which should greatly speed the licensing process and further reduce costs. Third, the low level of induced radioactivity simplifies the decommissioning of the end of plant life.

In the D-^{3}He cycle, a large fraction of the reaction energy appears in the form of charged particles and synchrotron radiation. In principle, each of these can be converted directly to d.c. electricity without the necessity of going through a thermal cycle. Thus, the efficiency can be very high; estimates of 60-70% appear to be realistic. This reduces the waste heat significantly, and results in smaller plant sizes for a given electric power output. Avoidance of the thermal cycle would also permit operation of the first wall and structural material at low temperature, where radiation damage is reduced.

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4. G. Kulcinski et. al., "Apollo - An Advanced Fuel Fusion Reactor for the 21st Century," University of Wisconsin Report UWFDM-780 (Oct. 1988).

The principal disadvantage of the D-^{3}He cycle is generally believed to result from its relatively low fusion power density. Because the fusion reaction cross section is smaller and the required temperatures are higher, the fusion power production rate per unit volume is about two orders of magnitude lower id D-^{3}He than in D-T, at a given magnetic field strength and value of β, where β is the ratio of plasma pressure to magnetic pressure. The fusion power density varies as β^2B^4. In low β devices such as Tokamaks ($\beta \leq 10\%$) this results in somewhat larger required plasma volumes and higher fields, for ignition in D-^{3}He than in D-T mixtures. In high β devices such as FRC's, however, where β = 60-90%, the fusion power density can be kept very high even with moderate magnetic fields, so that other factors determine the reactor size. These tradeoffs are illustrated in examples given in the following sections.

We now turn from the generic advantages of the D-^{3}He fusion cycle to a brief discussion of the relative advantages of two confinement approaches, the Tokamak and the FRC.

IV. D-^{3}He TOKAMAKS

The Tokamak represents the conventional, most developed low-β approach to magnetic fusion. There have been two fairly detailed studies of D-^{3}He based Tokamaks, the Apollo design (4) from the University of Wisconsin, and "case 8" of the ESECOM (3) study, which compared fission, D-T fusion, and D-^{3}He fusion. We use the former to illustrate general features. The most important parameters are listed in Table II. Tokamaks are toroidal magnetic traps, and have achieved higher temperatures and confinement parameters than any other approach. Scaling laws tend to make them fairly large, typically > 2500 MW (thermal). Due to their low β values, dictated by stability considerations, they operate at relatively high magnetic field strengths, particularly when D-^{3}He is the fuel cycle.

Because of the high magnetic field permeating the plasma, a large fraction of the energy loss is in the form of synchrotron radiation, which is narrow band and can in principle by converted directly to electricity at high

efficiency by using rectifying antennas ("rectennas"). Rectennas which would operate at the required frequencies are currently under development. Thus, the D-^{3}He Tokamak should be able to operate at relatively high plant efficiencies, and it may even be possible to dispense entirely with the usual thermal conversion cycle. Such an approach has been adopted for some of the Apollo cases. Typical parameters for an Apollo design are shown in Table II. It is not considerably larger than competing D-T tokamaks, due to the use of high field magnets, and space savings accomplished by reduced radiation shielding requirements. The plasma current, while large, is driven primarily by synchrotron radiation and the "bootstrap" effect, and requires only modest external current drive. Of particular interest and importance is the very low neutron wall loading, of 0.1 MW/m^2, allowing for a 1st wall which does not need to be replaced during the reactor lifetime.

V. D-^{3}He FRC's

The FRC is a linear device with closed poloidal field lines and no toroidal field, as shown schematically in Fig. 2. As a result its β value is between 70% and 90%, providing very high fusion power densities at modest field strengths of typically 4-9 Tesla, well below state-of-the-art. FRC physics is less advanced than that of Tokamaks. However, experimental FRC research in the last decade has produced energetic, stable plasmas with very good confinement parameters. Larger, proof-of-principle experiments are presently under construction.

The only studies carried out for FRC reactors were simple conceptual designs done 5-9 years ago,[5 6 7] so that it is not possible to make detailed quantitative cost estimates such as have been done for D-^{3}He Tokamaks. However, the higher fusion power density of FRC's would be expected to result in slightly lower cost of electricity than for Tokamaks,

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5.G. Miley et. al., The SAFFIRE Reactor Concept, EPRI Report AP-1437, (1980)

6.R.L Hagenson and R.A. Krakowski, The CTOR Reactor, Los Alamos Report LA-8758-MS (1981)

7.G.C. Vlases et. al., Fusion Technology 9 116 (1986)

based on generally accepted principles of fusion reactor design. Although no detailed FRC designs exist, simple plasma physics models of a D-^{3}He reactor can be used to illustrate important features of an FRC reactor. These are shown in Table II and illustrate the substantial differences between Tokamak and FRC designs.

Two cases are shown. The first is very field (4T) design and achieves power densities and first wall fluences similar to those of Apollo in a slightly smaller volume. The second design is a very compact, high power density system in which the unit size can be quite small. Although the wall neutron load here is higher, it is still an order of magnitude lower than for a D-T Tokamak, and thus first wall replacement would occur only once every 10-15 years.

Synchrotron losses in an FRC are quite low due to the high β, so that power extraction schemes would probably concentrate on direct conversion of the charged particle energy. If a thermal cycle is used, the particle heat load on the wall can be reduced as much as desired by using the natural divertor geometry to advantage. The D-^{3}He FRC looks to be particularly attractive for space power and propulsion applications by virtue of its very high power density, reduced shielding requirements, and reduced radiator mass.

VI. CONCLUSIONS

Both Tokamaks and FRC's offer certain advantages, and the ultimate decision as to which to pursue for terrestrial power generation will depend heavily on how the physics performance of each of them develops over the next few years. Whether the final choice is for Tokamaks, FRC's, or other confinement approaches such as Stellarators, Reversed Field Pinches, or Mirrors, it is clear that the D-^{3}He fuel cycle offers clear advantages over the D-T cycle. Although the physics requirements for D-^{3}He are more demanding, the overwhelming advantages resulting from the two order of magnitude reduction of neutron flux is expected by many fusion reactor designers to lead to a shorter time to commercialization than for the D-T cycle.

Table 1

	D-T Cycle	D-^{3}He Cycle
Advantages	High Fusion Power Density	Very Low Neutron Fluence, Which Implies:
	Easier Ignition	o Reactor Lifetime 1st Wall
	Readily Available (Terrestrial) Fuel Supply	o Low Activation
		o Easier Licensing
		High Fraction of Directly Convertible Reaction Energy
Disadvantages	Difficult Materials Problems	Lower Fusion Power Density
	Frequent 1st Wall Changeout	No Terrestrial ^{3}He
	Some Afterheat Problem	
	Requires Thermal Cycle	
	More Difficult De-Commissioning	

SCHEMATIC OF TOKAMAK REACTOR CORE

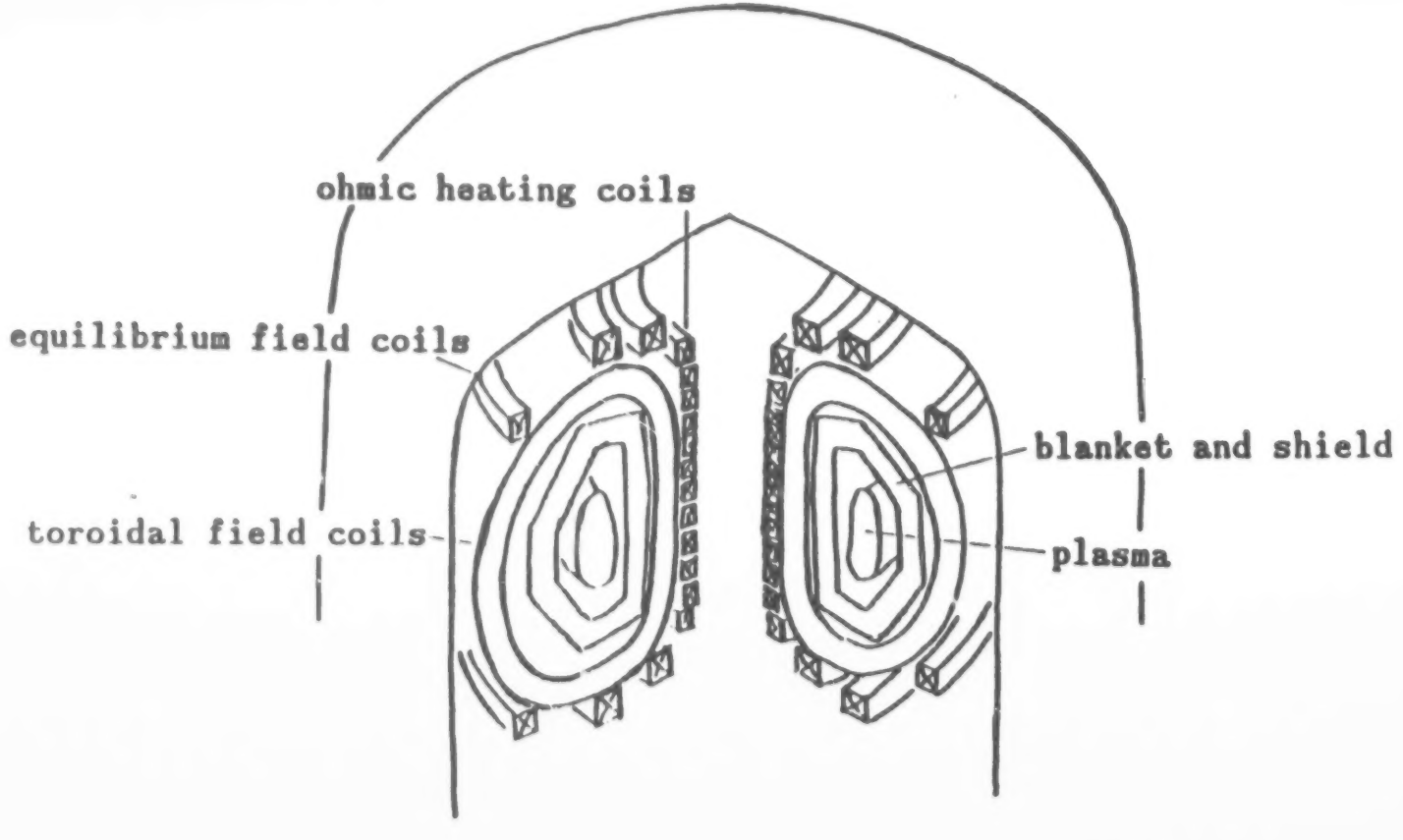

Figure 1

SCHEMATIC OF FRC REACTOR CORE

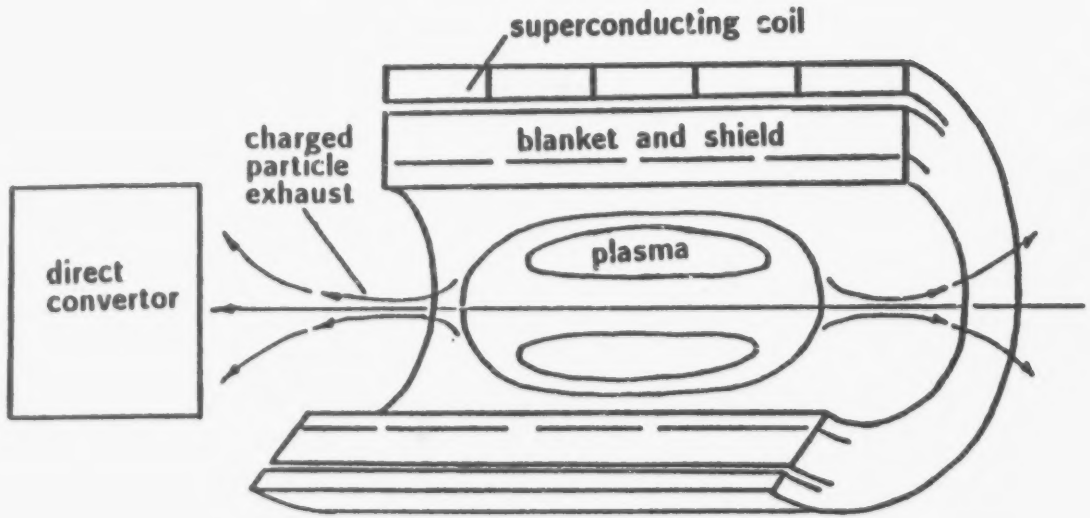

Figure 2

COMPARISON OF D-^{3}He TOKAMAK AND FRC REACTOR PARAMETERS: POWER FLOW CHARACTERISTICS

	TOKAMAK (APOLLO DESIGN)	FRC LOW-B	FRC HIGH-POWER DENSITY
Overall Power Production			
Fusion Power (MW)	2872	3072	254
Electric Power (MW)	1200	1200	100
Breakdown of Power Types (MW)			
Charged Particles	287	1524	119
Neutrons	118	66	6
Synchrotron Radiation	1626	258	29
Bremsstrahlung Radiation	959	1224	101
Wall Loadings			
Neutron Loading (MW/m^2)	0.10	0.12	0.21
Radiant Loading (W/cm^2)	91	250	500
Fusion Power Density (MW/m^3)	2.03	4.6	30

Table II, part 1

COMPARISON OF D-^{3}He TOKAMAK & FRC REACTOR PARAMETERS: PLASMA & FACILITY SIZE PARAMETERS

	TOKAMAK (APOLLO DESIGN)	FRC LOW-B	FRC HIGH POWER DENSITY
Magnetic Fields			
at coil (T)	20	5	8
at plasma (T)	12.9	5	8
Plasma Size and Shape			
Major Radius (m)	8	1.9	0.54
Minor Radius (m)	2.0	0.8	0.22
Volume (m^3)	1410	670	8.4
Aspect Ratio	4	(1)	(1)
Elongation	2	5.4	3
Plasma Parameters			
Ion Temperature (keV)	69	80	80
Ion Density ($10^{20} m^{-3}$)	1.3	2.3	5.8
Average Beta	0.06	0.9	0.9
$n\tau_E$ ($10^{20} m^{-3} s$)	48	17	18

Table II, part 2

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THE SOLAR POWER SATELLITE (SPS) - PROGRESS SO FAR

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INTRODUCTION

During the 1980's, public interest in large-scale alternative energy sources waned with the apparent availability of affordable fossil fuels. However, the environmental risks associated with combustion (the "Greenhouse Effect") and exploitation of non-renewable energy sources in ecologically fragile areas are a source of public concern on an international level. It is appropriate, therefore, that there be an assessment of alternative energy technologies and the potential use of extraterrestrial resources to provide decision makers with an understanding of the energy options available to them in the coming decades. One promising alternative option is the Solar Power Satellite (SPS)[1].

The objective of the SPS is to convert solar energy in space for use on Earth. Its most significant benefit is the potential for continuously generating large-scale electric power for distribution on a global basis. While, there has been no SPS development program in the United States since 1980, it has continued to be investigated in the Soviet Union, Europe, and Japan. In addition there has been very significant progress in SPS-related technologies, including solar cells, power beaming, structures and space transportation. The current and projected developments in the build up of the space infrastructure could have a positive impact on the overall feasibility of the SPS not only by supplying commodity materials from the moon[2],[3], but by developing intermediate markets for power in space (e.g., energy for the Space Station, free-flying platforms and for lunar and planetary bases).

The objectives of this review are to outline the major developments in key SPS-related technologies and to evaluate the significance of these developments to the consideration of the SPS, both as an alternative energy option for use on Earth and as a potential stimulus for space infrastructure developments, and the use of extraterrestrial resources.

BACKGROUND

In the 1970's, SPS assessments were performed by NASA and the U.S. Department of Energy, the Congressional Office of Technology Assessment, and the National Research Council, National Academy of Sciences.[4] These assessments considered technical, economic, environmental and societal issues. In preliminary studies of the SPS concept (1968 to 1972), a plan for an SPS R & D

1 P.E. Glaser, "Power From the Sun: Its Future," Science, 162, 857-866 (1968).

2 E. Brock, Lunar Resource Utilization for Space Construction, Final Report, General Dynamics, Convair Division, NASA, JSC, Houston, Texas, NAS9-15560 (1979).

3 P. DuBose, "Solar Power Satellite Built of Lunar Materials," Space Power, Vol. 6,1986, pp. 1-98.

4 National Research Council, Electric Power From Orbit, a Critique of a Satellite Power System, July 1981.

program was outlined[5]. In 1974, a feasibility study was undertaken to evaluate an SPS design for a power output of 5 GW for use on Earth[6]. This feasibility study identified key technological, environmental and economic issues for further study and provided the foundation for more extensive system definition studies[7,8,9]. A preliminary assessment of the SPS concept resulted in the SPS Concept Development and Evaluation Program Plan[10], which had as its objective: "To develop, by the end of 1980, an initial understanding of the technical feasibility, economic practicality, and societal and environmental acceptability of the SPS concept."

THE SPS SYSTEM

As originally conceived[11] an SPS could utilize various approaches to solar energy conversion, such as photovoltaic and thermal-electric. Among these conversion processes, photovoltaic conversion was selected as a useful starting point because solar cells were already in wide use in communication, Earth observation and meteorological satellites, both in low-Earth orbit (LEO) and in geosynchronous orbit (GEO). Since then, an added incentive has been the substantial progress being made in the development of advanced photovoltaic materials, microwave and laser power beaming, and the increasing confidence in the achievement of significant cost reductions in space transportation and use of lunar materials.

In the baseline SPS concept, solar cell arrays would convert solar energy directly into electricity and feed it to microwave generators forming part of a planar, phased-array transmitting antenna. The antenna would direct a microwave beam of very low power density precisely to one or more receiving antennas, at desired locations on Earth. At the receiving antennas, the microwave energy would be safely and efficiently reconverted into electricity and then transmitted to users. An SPS system could consist of many satellites Earth orbits, e.g., in GEO, each SPS beaming power to one or more receiving antennas at desired locations.

The SPS Orbit

The most favorable orbit for solar energy conversion would be an orbit around the Sun. However, at this stage of space technology development, GEO represents a reasonable compromise because solar radiation received in GEO - unlike solar radiation received on Earth - is available 24 hours each day during most of the year. Solar radiation intercepted by a satellite in GEO will be interrupted by Earth eclipses of the Sun for 22 days before and 22 days after the Equinoxes. The

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5 National Science Foundation, An Assessment of Solar Energy as a National Resource, NSF/NASA Solar Energy Panel, University of Maryland, College Park, MD (1972).

6 P.E. Glaser, O.E. Maynard, J. Mockovciak, Jr., and E.L. Ralph, Feasibility Study of a Satellite Solar Power Station, NASA Lewis Research Center, Cleveland, Ohio, CR-2357, NTIS N74-17784 (1974).

7 ECON, Inc., Space-Based Solar Power Conversion and Delivery Systems Study, Final Report, NASA, MSFC, Huntsville, Alabama, NAS8-31308 (1977).

8 Boeing Aerospace, Solar Power Satellite System Definition Study, Final Report, Vol. I-VII, for NASA, JSC, Houston, Texas, NAS8-32475 (1980).

9 Rockwell International, Satellite Power System (SPS) Concept Definition Study. NASA, MSFC, Huntsville, Alabama, NAS8-32475 (1980).

10 U.S. Department of Energy, Satellite Power (SPS) Concept Development and Evaluation Program Plan: July 1977 - August 1980, DOE/ET-0034, U.S. Government Printing Office, No. 061-000-00031-3, Washington, D.C. (1978).

11 P.E. Glaser, "Method and Apparatus for Converting Solar Radiation to Electrical Power", U.S. Patent No. 3,781,647 (1973).

maximum period of interruption, occurring when the Earth, as seen from a GEO position is near local midnight, will be 72 minutes a day. Overall, eclipses will reduce the solar energy received in an orbital position in GEO by about 1% of the total available during a year. With this year-round conversion capability, the SPS could be used to generate base load power on Earth with minimal requirement for energy storage. Furthermore, the absence in space of environmental and gravitational constraints on the erection of light-weight, extensive, contiguous structures would permit the deployment of the SPS over large areas. Micrometeoroid impacts are projected to degrade 1% of the SPS area over a 30-year exposure period. Because of the small probability of impact, large meteoroids are not likely to affect the SPS components in GEO.

The Solar Energy Conversion Process

Several photovoltaic energy conversion processes are applicable to the SPS concept. Both flat arrays of single crystal silicon, and gallium arsenide solar cells with solar concentration[12] have been evaluated. Significant progress is being achieved in the development of mono-and polycrystalline, thin-film, multijunction and heterojunction solar cells as indicated by subjects discussed at major conferences, so that further performance improvements can be projected[13], [14].

The solar cells should have as high an efficiency as possible, a low mass per unit area, and be resistant to radiation during transit to, and operation in, GEO. To extend the lifetime of the solar cells, *in situ* annealing methods have been considered, including heating with solar concentrators to reduce the degrading effects of accumulated radiation exposure.

Power Transmission From Space to Earth

Microwave beams or laser beams could be used to transmit the power generated in the SPS to suitable receivers on Earth. Laser power transmission is an interesting possibility because of considerable advances in laser technology[15] and the ability to deliver power in amounts as low as 100 MW to receiving sites on Earth.

o **Microwave Transmission**

Microwave power transmission has received most attention, based on considerations of technical feasibility, fail-safe design, and low flux levels. Free space transmission of power by microwaves is not a new technology[16]. The system efficiencies for the interconversion (d.c.-to-microwaves-to-d.c. at both terminals of the transmission system) have already been demonstrated to be 54%; a further improvement to 70% is projected. The general belief about microwave power transmission is that it is an emerging technology which has to rely on fragile and short-lived, as well as expensive and low-power, components. In fact, the conversion of d.c.

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12 Rockwell International, Advanced Satellite Power System Concept, PD 80-61, Rockwell International, Downey, CA (1980).

13 Solar Energy Research Institute, 9th Photovoltaic Advanced Research and Development Project, May 24-26, 1989, Lakewood, CO.

14 Commission of the European Communities, 9th European Photovoltaic Solar Energy Conference, Sept. 25-29, 1989, Freiburg, FRG.

15 NASA, Langley Research Center, Second Beamed Space Power Workshop, 28 February to 2 March, 1989, Hampton, VA

16 W. C. Brown, Experimental Airborne Microwave Supported Platform, Technical Report, Rome Air Development Center, Rome, NY, TADC-TR-188 (1965).

to r.f. power at microwave frequencies has led to the establishment of a major industrial capability to produce devices to meet consumer and industrial requirements. Several microwave generators, including linear beam devices, klystrons, gyrotrons, solid-state amplifiers, and cross-field devices, amplitrons and magnetrons, could be used. Magnetron developments indicate that a microwave generation subsystem based on the magnetron would have better performance and a smaller mass.[17]

The microwave generators are incorporated in the transmitting antenna, which is designed as a circular, planar, active, slotted, phased array. Space is an ideal medium for the transmission of microwaves: a transmission efficiency of 99.6% would be achievable after the beam has been launched at the transmitting antenna and before it passes through the upper atmosphere. To generate 5 GW, assumed for the NASA SPS reference system[10], the transmitting antenna would be about 1 km in diameter and the receiving antenna would be an ellipse about 10 by 13 km at 40° latitude. A peak power density of 23 $mWcm^{-2}$ at the receiving antenna would obviate heating of the ionosphere. The microwave power beam could be shaped so that the power density at the edges of the receiving antenna would be 1 $mWcm^{-2}$, and only 0.1 mW cm^{-2} at the receiving antenna site perimeter, about 1 km beyond the receiving antenna.

The transmitting antenna is divided into a large number of subarrays. A closed-loop retrodirective array with a phase-front control system could achieve the high efficiency, pointing accuracy and safety essential for the microwave beam operation. In the retrodirective array design, a coded reference signal is beamed from the center of the receiving antenna to the transmitting antenna. With this design, it is physically impossible for the microwave beam to be directed to any other location on Earth but the receiving antenna.

The receiving antenna has been demonstrated to intercept, collect, and rectify the microwave beam into d.c. with an efficiency of 85%.[18] The d.c. output interfaces with either high-voltage d.c. transmission networks or is converted into 60 Hz a.c. The receiving antenna consists of an array of elements which absorb and rectify the incident microwave beam. Each element consists of a dipole, an integral low-pass filter, a diode rectifier and a bypass capacitor. The dipoles are d.c.-insulated from the ground plane and appear as r.f. absorbers to the incoming microwaves. The collection efficiency of the receiving antenna is insensitive to substantial changes in the direction of the incoming beam. Furthermore, the efficiency is independent of potentially substantial spatial variations in phase and power density of the incoming beam that could be caused by nonuniform atmospheric conditions. Under normal atmospheric conditions, attenuation and scattering of the microwave beam will result in a loss of about 2%. Under the worst weather conditions the total loss could be as high as 8%.

The amount of microwave power received in local regions of the receiving antenna can be matched to the power-handling capability of the microwave rectifiers. The rectifiers, which could be gallium arsenide Schottky barrier diodes, have a power-handling capability several times that required for this application. Any heat resulting from inefficient rectification in the diode and its circuit can be convected by the receiving antenna to ambient air, producing atmospheric heating

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17 W. C. Brown, Satellite Power System (SPS) Magnetron Tube Assessment Study, Final Report, NASA, MSFC, Huntsville, Alabama, NAS8-331578 (1980).

18 R. M. Dickinson and W. C. Brown, Radiated Microwave Power Transmission System Efficiency Measurements, Technical Memorandum 33-727, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (1979).

which will be only about twice that of the heat release of a typical suburban area. The low thermal pollution resulting from the microwave power rectification process cannot be equalled by any known thermodynamic conversion process for power generation.

The receiving antenna could be designed to be 70% transparent to sunlight. Microwaves can be excluded from beneath the antenna by a grounded mesh enclosure. A large number of potential sites for receiving antennas can be identified. However, for each site environmental impacts will have to be assessed before constructing a receiving antenna[19]. Design concepts for offshore receiving antennas include floating structures for installation in continental shelf waters and bottom-mounted structures which could be deployed in shallow waters.[20] Offshore receiving antennas could be constructed near major population centers which are located near sea coasts in many countries around the world. They could be designed to permit secondary operations beneath the antenna, for example, mariculture with on-site docking and processing facilities to provide a significant source of fish protein. One such site could meet up to about 5% of the present US demand for fish protein.

o **Laser Transmission**

Concentrated and dispersed beams generated by continuous-wave, electric-discharge lasers with recirculating gas have been considered[21]. Gas circulation permits the removal of waste heat and minimizes consumption, thus allowing extended operations. Although carbon dioxide and carbon monoxide electric discharge lasers have reached an advanced state of development, other laser concepts, including free-electron lasers, diode laser arrays, and solar-pumped lasers, are being developed. Power may be supplied to these lasers by solar photovoltaic and nuclear thermal conversion, or through direct excitation by solar radiation.

Photovoltaic cells, compositionally tuned for high efficiency[22], could be used to convert laser beam radiation at the receiving site on Earth. If successfully developed, tuned optical diodes, which are the analog of microwave diode rectifiers but operate in the infrared portion of the spectrum, may be used to convert laser radiation into a d.c. output. Thermodynamic cycles could also be used when efficient laser heat absorption systems have been developed.

Atmospheric absorption of laser radiation would be reduced when the receiving sites are located at high elevations, but even in such locations unfavorable weather would require that the laser radiation be beamed to receiving sites with more favorable weather conditions and fed into a shared transmission grid. The dimensions of a laser radiation receiving site, including a safety zone, could be measured in hundreds of meters against the thousands of meters needed for a microwave beam receiving antenna.

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19 Environmental Resources Group, Prototype Environmental Assessment of the Impacts of Siting and Constructing a Satellite Power System (SPS) Ground Receiving Station (GRS) DOE/ER-0072, NTIS, August 1980.

20 J. W. Freeman, Solar Power Satellite Offshore Rectenna Study, Contractor Report 3348, Rice University for NASA, MSFC, Huntsville, Alabama, NAS8-33023 (1980).

21 R. E. Beverly, SPS Laser Systems Analysis and Environmental Concerns, Rockwell International Corporation, Downey, California, NAS8-3475 (1979).

22 Gilbert H. Walker, Photovoltaic Conversion of Laser-to-Electric Power, Proceedings of 18th IECEC, August 1983, pp. 1194-1199.

Although laser power transmission is still in an early stage of development, and significant technology advancements will be required, there is considerable promise in a laser power transmission system for the SPS. Environmental impacts, including heating of the atmosphere and meteorological effects, are not expected to be significant, although the plasma chemistry of the upper atmosphere and induced reactions will require further study. The potential for interference with communication links will be greatly reduced. Requirements for safety and security of laser power transmission could be adequately met, however, there would have to be safeguards to prevent misuse of laser power.

Space Transportation

To be commercially competitive, the SPS will require a space transportation system capable of placing payloads into LEO and GEO at the lowest possible cost. The space transportation system which will be available during the early phases of SPS development for technology verification and component functional demonstration will be an advanced version of the Space Shuttle, and subsequently an advanced launch system now under study.

As part of the SPS system studies, various space transportation systems concepts have been considered.[8,9] including advanced shuttles, launch vehicles utilizing shuttle components and a variety of advanced heavy lift launch vehicles, including ballistic single-stage and two-stage vehicles or winged two-stage vehicles for easy recovery. Such vehicles could transport payloads ranging from 100 to 300 tons into LEO and would be recoverable and repeatedly reusable. In the two-stage vehicles, the fuel for the lower stage would be liquid oxygen and a hydrocarbon; liquid oxygen and liquid hydrogen would be used for the upper stage.

Both offshore and onshore launch facilities have also been considered. For example, an offshore launch facility constructed near the Equator would reduce launch costs and eliminate the noise impact of frequent launches in populated regions. To achieve a projected cost of $50 per kg for launching SPS payloads would require turn-around maintenance and mission control procedures similar to those employed in commercial airline operations.

Personnel and cargo would be transported from LEO to GEO with chemically or electrically propelled vehicles which would not need to reenter the atmosphere. Ion thrusters of high specific impulse would be powered by solar cell arrays. Although the transit time to GEO would be measured in months, ion thrusters would minimize the amount of propellant to be transported to LEO.

The development of advanced space transportation systems is proceeding. The cost of orbiting payloads is projected to drop from thousands of dollars per kilogram for the space shuttle to less than a hundred of dollars per kilogram for an advanced space transportation system[23].

These cost projections appear to enhance the competitiveness of an SPS as compared to currently known energy sources. However, the transportation of the required materials from Earth on the scale required to build up a global SPS system may result in undesirable environmental effects, as propellant combustion products will be deposited at various levels in the atmosphere. Therefore, it may be advantageous to obtain commodity materials required for the construction of the SPS from the moon especially if processing and transportation of materials from the moon to GEO could be accomplished at costs comparable to launches of payloads from Earth.

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23 U.S. Department of Energy, Satellite Power Systems (SPS) Space Transportation Cost Analysis and Evaluation, DOE/ER-0086, November 1980. (NTIS)

Orbital Assembly And Maintenance

The absence of gravity and of the influence of forces shaping the terrestrial environment, presents a unique freedom for the design of extensive orbiting structures, their fabrication, assembly and maintenance in LEO and/or in GEO.

In a selected orbit the function of a structure is to define the position of components rather than to support loads. The loads, under the normal operating conditions, are orders of magnitude less than those experienced by structures on the surface of the Earth. The structure will have to be designed to withstand loads imposed on discrete sections during assembly into a continuous structure. Attitude control will be required to direct the solar energy conversion system towards the Sun and the transmitting antenna towards the receiving antenna on Earth. This configuration will require that the transmitting antenna rotate once a day with respect to the solar energy conversion system. The extensive structures envisioned for the solar energy conversion system and the transmitting antenna will undergo large dimensional changes as a result of significant temperature variations imposed during periodic eclipses. Composite materials can be considered for the structure because they have a small coefficient of thermal expansion compared to aluminum alloys.

The contiguous structure which would be required for the SPS is of a size which has never been fabricated on Earth. Therefore, automated construction methods will be required to position and support the major components such as the solar arrays forming part of the solar energy conversion system and the microwave subarrays forming the transmitting antenna. For example, an automated beam builder has already been demonstrated on Earth.

Warehousing logistics and inventory control will be required to manage the flow of material to the SPS construction facilities which will be located in LEO and GEO. The construction facility could be a space station which would also provide launch and docking facilities and a habitat for crew members.

SPS GROWTH PATH

An optimized SPS design has not yet been developed. However, to analyze technical issues, evaluate environmental effects, explore societal concerns and perform comparative assessments, an SPS reference system based on assumed guidelines was established.[24] The SPS reference system was based on the use of either single crystal silicon flat arrays or gallium arsenide solar cells in combination with solar concentrators.

The complete SPS system includes not only the satellite but also the following space construction and support systems:

- o A base in LEO for electric orbit transfer vehicles, for servicing space transportation systems, and for logistics support;
- o An assembly station in GEO for constructing the SPS, and
- o A GEO support base for the robotic systems that provide service and periodic maintenance for an operating SPS.

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24 U.S. Department of Energy, Satellite Power System Concept Development and Evaluation Program -- Reference System Report, DOE/ER-0023 (1978).

The objective of the SPS is to generate base load electrical power for use on Earth. Assuming that a global SPS system is planned to be placed in operation after the year 2010, it is most likely that at first it would be designed to replace existing power plants and to add new generating capacity to meet future energy demands in both developed and developing countries. This role for the SPS would only be possible if it could generate competitively priced electricity in the context of future energy demands.

The build up of the global SPS system would be time-phased to gain confidence in its effective performance and the realizability of projected construction costs. A modest number of SPSs could be placed in operation in the first quarter of the 21st century to demonstrate the commercial feasibility of the SPS. Only after the necessary operating experience has been obtained could a more rapid growth in the SPS contribution to future energy demands be expected. The rate of growth of a global SPS system would be determined by the development of efficient electricity demand technologies and by the economics of this system relative to alternative energy technologies.

Thus far, studies[25] have shown that there are no likely show stoppers in an SPS program. They have, however, identified technical, economic, environmental and societal issues which require more detailed definition. The cost estimates for the SPS reference system, rough as they are and subject to criticism as they may be, fall in a potentially interesting range. They are sufficiently competitive to justify, not a major commitment at this time, but a continued analysis, research and technology verification program of the SPS.

An approach can be devised for the development of the SPS that identifies the underlying generic technologies and their application to specific space power projects, as shown in Figure 1. The "terracing" of space power projects would reduce the challenges typically associated with large-scale projects, including the control of the project, the effects of technical uncertainties, maintenance of investor confidence, reduction of environmental impacts, and the difficulties associated with termination of the project if warranted. The increasing capabilities needed for planned space projects - free-flying carriers, manned space stations, and space transportation systems of higher performance and lower cost-will contribute to the industrial infrastructure that could be the foundation for SPS development.

Projects such as the SPS are unlikely to be pursued until information from space power projects at successive "terrace" levels can guide the evolution of the most appropriate design for the SPS.

The assumption underlying the "terracing" approach is that advanced technologies will be developed in support of national and international space projects. For example, some of the technologies that will be required for the SPS are already being developed for a variety of space applications.

There is every indication that advanced technologies and space infrastructure elements could lead to the development of an even more competitive SPS system, particularly if a lunar base and processing of lunar resources were to be realized.

SPS Economics

The economic justification for an SPS development program must acknowledge that it is not possible to know now the cost of a technology which will not be fully developed for at least 15 years or commercialized in less than 20 years. Justification is equally difficult to provide for other advanced energy technologies.

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25 U.S. Department of Energy, Program Assessment Report Statement of Findings, DOE/ER-0085 (1980).

Cost-effectiveness analyses alone are inappropriate because they would require the extremely difficult task to postulating credible scenarios of the future. The near-term decisions regarding the conduct of the SPS program should therefore be based on the resources allocated to the SPS research tasks and their priorities rather than the projected economics of the SPS in the 21st century.

Cost projections do not provide meaningful estimates of the potential market penetration of the SPS or alternative energy supply technologies because the uncertainties in forecasting prices are much larger than the cost differentials on which the cost comparisons among competing technologies will eventually be based. However, such cost studies provide estimates of the delivered cost of power to indicate whether the SPS has any chance of being competitive, identify the major cost elements so that program efforts can be properly focused to reduce the projected costs, develop a consistent framework to evaluate different technological options, determine the impacts of raw material requirements and availability on cost and the effects of a development program on labor costs and capital markets and assess the cost risk in comparison with alternative energy supply technologies, including environmental impacts and societal effects.

The SPS was compared with alternative energy technologies, including coal, nuclear and terrestrial photovoltaic systems, in terms of cost and performance, health and safety, environmental effects, resource requirements, and institutional issues.[26] The assessments indicated that:

- The life-cycle cost range for the SPS overlaps the competitive cost ranges of alternative energy technologies;
- All the technologies considered will have distinct, though different, health and safety impacts;
- The low-level and delayed impacts of all energy technologies are difficult to quantify and assess;
- Each technology has material requirements that could be critical, because of environmental control standards or limited production capability; however, these requirements do not appear to limit the SPS;
- The total amount of land required for the complete fuel cycle is roughly the same for all energy technologies; however, the SPS and terrestrial centralized photovoltaic systems would require large contiguous land areas;
- The SPS, fusion and other advanced energy technologies may be difficult to operate within the current regulatory environment; however, the SPS could also be subject to international regulations that do not appear to limit the other technologies.

SPS Assessment Issues

The SPS program is unique in that for the first time a technology assessment program focused not just on key technology issues but was also concerned with environmental effects, comparative economic factors, societal issues and program risks and uncertainties before any commitment to a development program was made[27]. Of these considerations the most significant non-technical issues were the SPS's environmental effects and resource requirements.

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26 M. R. Riches, A Comparative Assessment of the Reference Satellite Power System with Selected Current, Near-Term and Advanced Energy Technologies, Department of Energy, Conference Report. 800491, 66-67 (1980).

27 F. A. Koomanoff and C. A. Sandahl, "Status of the Satellite Power System Concept Development and Evaluation Program", Space Solar Power Review, 1, 67-77 (1980).

Environmental Effects

The key environmental effects associated with the SPS are those which could affect human health and safety, ecosystems, climate, and interactions with electromagnetic systems.

o **Health and Ecological Effects of Microwave Power Transmission**

At the perimeter of a receiving antenna, the public would be exposed to microwaves at a power density of 0.1 mW cm^{-2}. If as assumed for the NASA SPS reference system, 60 receiving antennas in the continental United States were spaced an average of 300 km apart, the minimum power density at any point would be about 10^{-4} $mWcm^{-2}$. At present, 1% of the population is potentially exposed to microwave power densities of 10^{-3} mWc^{m-2}. In the USSR, the maximum value for continuous, 24-hour, exposure of the general public is estimated to be 10^{-3} $mWcm^{-2}$. The US population is experiencing a medium exposure value of about 10^{-6} $mWcm^{-2}$ for a time-averaged microwave power density. The workers within the receiving antenna area would not be exposed to levels exceeding U.S. guidelines for occupational exposure with suitable precautionary measures.

The fact that large populations are exposed to microwave energy from communications, medical, radar and industrial processes for many decades and, more recently, from microwave cooking, without demonstrated adverse effects on human health and the ecosystem, is an indication that microwaves beaming from space to Earth is unlikely to result in undesirable health and ecological effects.

o **Non-microwave Health and Ecological Effects**

Among the various space-related activities only the exposure of the space workers to ionizing radiation appears to present a major health risk. Most of the other health and ecological effects of the construction and operation of receiving antennas and launch sites have conventional impacts which would be controlled or mitigated by appropriate engineering changes and are analogous to developing and constructing alternative energy sources.

The risks from ionizing radiation to space workers could be minimized through carefully designed shielding for space vehicles, for working and living modules and by the provision of solar storm shelters. Of greatest concern are the high-energy, heavy ions in GEO which may result in exceeding recommended exposure limits for workers. More data are required to establish the expected ionizing radiation environment in GEO to guide the design of measures to limit exposure of space workers.

o **Effects on the Atmosphere**

Weather and climatic effects of waste heat released at a receiving antenna site would be generally small, comparable to the heat released over suburban areas. The absorption of microwave power in the troposphere is expected to increase during heavy rainstorms, but even then would have only a negligible effect on the weather. The air quality effect of the launch of advanced space transportation vehicles, which would increase sulphur dioxide concentration, would not be critical. Nearly all of the carbon monoxide would be oxidized to carbon dioxide, and the amount of nitric oxides formed would be negligible. Some acid rain might occur near the launch site if there are significant quantities of sulphur in the fuel. Inadvertent weather modification by rocket effluents in the troposphere, because of cumulative effects, would be possible and would require continuing monitoring of rocket exhaust clouds and the various meteorological conditions to mitigate such effects.

Carbon dioxide emissions if carbohydrate-based propellants are used would be expected to add to the "greenhouse" effect. The change in the globally averaged ozone layer due to SPS launches would be undetectable as would the effects of nitrogen oxides. Transient clouds at stratosphere and mesosphere altitudes could be induced in the vicinity of the launch site, but they would not be expected to have a detectable impact.

The effect of rocket launches on the ionosphere could be mitigated by a depressed launch trajectory: for example, a winged booster returning below an altitude of 75 km would keep the rocket effluents in the turbulent mixing regions of the atmosphere, reduce the possibility of hydrogen diffusion into the ionosphere and prevent the formation of noctilucent clouds. Optimization of the first stage's launch trajectory would reduce the injection of water vapor into the lower atmosphere if hydrogen-oxygen propellants are used, however, water vapor deposited in the upper atmosphere will have a long residence time and may result in undesirable effects if large quantities of water are deposited over an extended time frame.

Ion thrusters controlling the position of the solar energy conversion system and the microwave transmission antenna would inject argon ions into the plasmaphere and magnetosphere. These effects are either unknown or uncertain. Their magnitude would have to be established and perhaps other ion-thruster propellants utilized to minimize any disturbance of the plasmasphere or changes in the magnetosphere interaction with solar wind.

o **Effects of Ionospheric Disturbance on Telecommunications**

The ionosphere is important to telecommunications because radio waves can be totally reflected and returned to the Earth's surface, depending on the ionospheric electron density, the frequency of the electromagnetic energy, the frequency of occurrence of electron collisions, and the strength of the geomagnetic field. Changes in the ionosphere can alter the performance of telecommunication systems, and small-scale irregularities can produce radio signal fading and result in loss of information. Ionospheric changes could result either from heating of the ionosphere by the microwave beam or the interactions with effluents from space vehicles. The effects of rocket exhaust effluents during launch can be reduced through appropriate trajectory control. However, during reentry of the winged booster and orbiter stages, ablative materials and oxides of nitrogen could affect a small portion of the ionosphere.

Experiments on the effects of microwave beam heating of the ionosphere have indicated that at a peak power density of 23 mW cm^{-2}, the microwave beam would not adversely affect the performance of telecommunication systems and that the power density could be doubled.[28] Because of equipment limitations, these experiments deposited power in the lower ionosphere comparable to the microwave beam power densities. Modified and expanded facilities would be required to simulate heating of the upper ionosphere, verify the existing frequency-scaling theories, and establish the effects of the microwave beam on the upper atmosphere. If no adverse heating effects are observed, the peak power density could be increased.

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28 W.E. Gordon and L.M. Duncan, "SPS Impacts on the Upper Atmosphere," Astronautics and Aeronautics, Vol. 18, 1980, pp. 46-48.

o **Electromagnetic Compatibility**

The SPS must be designed and operated to satisfy established national and international rules for using the electromagnetic spectrum. There is a potential for producing interference because the amount of microwave power transmitted from space to Earth would be unprecedented and the size of the microwave beam would be very large at the Earth's surface. It could interfere with military systems, public communications, radar, aircraft communications, public utilities, transportation systems communication, other satellites, as well as radio and optical astronomy. The interference potential of the microwave beam would not be especially unusual except in the extent of the geographic area affected. High-powered radar systems produce interference of similar electromagnetic intensities, but over limited areas. Shielding and radio receiver filters are commonly used to avoid interference and could be adapted for this purpose.

The dimension of SPS-caused interference by direct energy coupling to any class of equipment is part of the engineering design of the microwave power transmission system and the receiving antenna. Interference can be minimized by designing the microwave system to stringent specifications, to reduce undesirable emissions at frequencies other than its operating frequency and to constrain the size and shape of the transmitted microwave beam. Careful receiving antenna siting, including tradeoffs between locations of the antennas near energy load centers, could avoid interference with most other users of the radio spectrum. SPS will not interfere with other satellites in GEO, such as communication satellites, because the microwave beam would deliver less than one-fifth the power that would be required to produce interference.

Radio and optical astronomical observations have to measure weak signals. Such observations could be significantly inhibited by the microwave power beam, even at distances of hundreds of kilometers from the receiving antenna sites. One mitigating approach would be to construct radio telescopes on the far side of the moon, where they would be shielded from all forms of terrestrially produced electromagnetic interference. Earth-based optical observations would be hindered by light reflected from the surfaces of an SPS, which would have a brightness approaching that of Venus when it is most visible. Orbiting astronomical observatories could be constructed which would provide better observational conditions than those obtainable even in the best locations on Earth. The cost of these mitigating approaches may have to be charged to the SPS system.

o **Resource Requirements**

The physical resource requirements which could present problems are land use, materials availability, and energy utilization.

o **Land Use**

Receiving antenna siting studies[29] showed that there are suitable locations for receiving antenna sites throughout the United States. The methodology developed for determining eligible areas for receiving antenna sites is widely applicable; however, actual acquisition of specific sites may be difficult, and location of sites in some areas could, because of their topography, incur a heavy cost

29 J.B. Blackburn, et al, "Satellite Power Systems Rectenna Siting: Availability of Nominally Eligible Sites", U.S. Department of Energy, 1980.

penalty for site preparation and perhaps even modifications of the receiving antenna designs. Studies showed that there are no apparent undesirable biological effects of microwaves on birds[30], selection of sites to avoid migratory bird flyways may be possible.

The sheer size and intensity of use of the contiguous land area required for a receiving antenna site and site construction will have significant implications for environmental, social and economic impacts and these will have to be established for each specific antenna site. In addition, the secondary uses of selected receiving antenna sites for agricultural purposes or for terrestrial solar energy conversion will need to be assessed.

The alternative of locating the receiving antenna offshore may be attractive for major population centers which are located near the sea coasts not only because of their possible proximity but also because floating offshore structures may be competitive with land-based structures and provide an opportunity for mariculture[20]. For example, the Northeast region of the US has the smallest potential land area for receiving antenna sites relative to projected needs.

o **Materials Availability**

An analysis of the materials requirements for the construction of the SPS indicated that no insurmountable materials supply difficulties are evident in terms of world and domestic supply and potential manufacturing capacity[31]. Over one-half the materials for the SPS reference system are readily available, but there are potential supply constraints on tungsten, silver and gallium. The industrial infrastructure to fabricate SPS components such as ion thrusters, dipole rectifiers, microwave generators, and graphite composites will be adequate; however, solar cell arrays will require development of mass production technologies, which could be used not only for the SPS but also to meet terrestrial photovoltaic system requirements.

o **Energy Utilization**

Net energy analysis is useful in comparing alternative energy technologies in terms of the energy produced by each system per unit of energy required. When fuel is excluded, the energy ratios for the SPS reference system are marginally favorable with respect to other energy production methods. When fuel is included, the SPS energy ratios are very favorable.[32] Using the technologies of the SPS reference system and estimates based on their probable improvements, energy payback periods for the SPS would be about one year.[33]

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30 Arthur D. Little Inc., Responses of Airborne Biota to Microwave Transmission from SPS. Report to Environmental Protection Agency, Research Triangle Park, N.C., 68-02-3278 (1980).

31 P.E. Glaser and P.K. Chapman, "The Emerging Infrastructure for the SPS", SPS Program Reviews Proceedings, U.S. Department of Energy, Conf. 800491, 1980, pp. 475-478.

32 R. R. Cirillo, Comparative Analysis of Net Energy Balance of Satellite Power System and Other Energy Systems, U. S. Department of Energy, DOE/ER-0056 (1980).

33 F. R. Livingston, Satellite Power System Environmental Impacts, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Report 900-822, Rev. A (May 1978, August 1978).

PROGRESS IN THE FUTURE

The SPS reference system that was the basis for assessments by NASA, U.S. Department of Energy, National Research Council and the Office of Technology Assessment[34] does no longer represent the current and projected state-of-the-art of space power. As Figure 1 indicates, an evolutionary development of the SPS concept to meet intermediate objectives with definable benefits is the most likely scenario for SPS development. It is possible now to project trends in technologies critical for SPS applications and to establish SPS development goals envisaged for a global SPS system. The SPS development goals are summarized in Table 1. Meeting these goals can achieve the vision of the National Commission on Space[35]: "Our ambition: Opening New Resource to Benefit Humanity".

CONCLUSIONS

- No single constraint has been identified which would preclude the resumption of an SPS program for either technical, economic, environmental or societal reasons.
- The SPS Reference System which assumed that 5 GW of base load power would be generated at the receiving antenna on Earth demonstrated that the technology for transmitting power from space to Earth is amenable to evolutionary development and that the SPS concept is technically feasible.
- Lunar resources including metals, glasses and oxygen promise to provide commodity materials for the construction of the SPS in GEO provided that the use of these resources can be competitive with terrestrial materials.
- Technology advances, performance improvements and projected cost reductions in, for example, solar cell arrays, large space structures, laser power transmission, microwave generators and rectifiers, and space transportation systems increase the technical feasibility and economic viability of the SPS concept.
- The significant progress that has been made as a result of broadly based technical, economic, environmental and societal studies on the SPS is resulting in a growing consensus that the SPS is one of the promising power generation options which could contribute to meeting global energy demands in the 21st century.
- The SPS concept has the potential, not only for baseload power generation on a global scale, but also represents an evolutionary direction for expanding human activities in space and the use of extraterrestrial materials.

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34 Office of Technology Assessment, Solar Power Satellites, OTA-E-144, August 1981.

35 National Commission on Space, Pioneering The Space Frontier, Bantam Books, 1986, p. 3.

Figure 1 POWER BEAMING GROWTH PATH

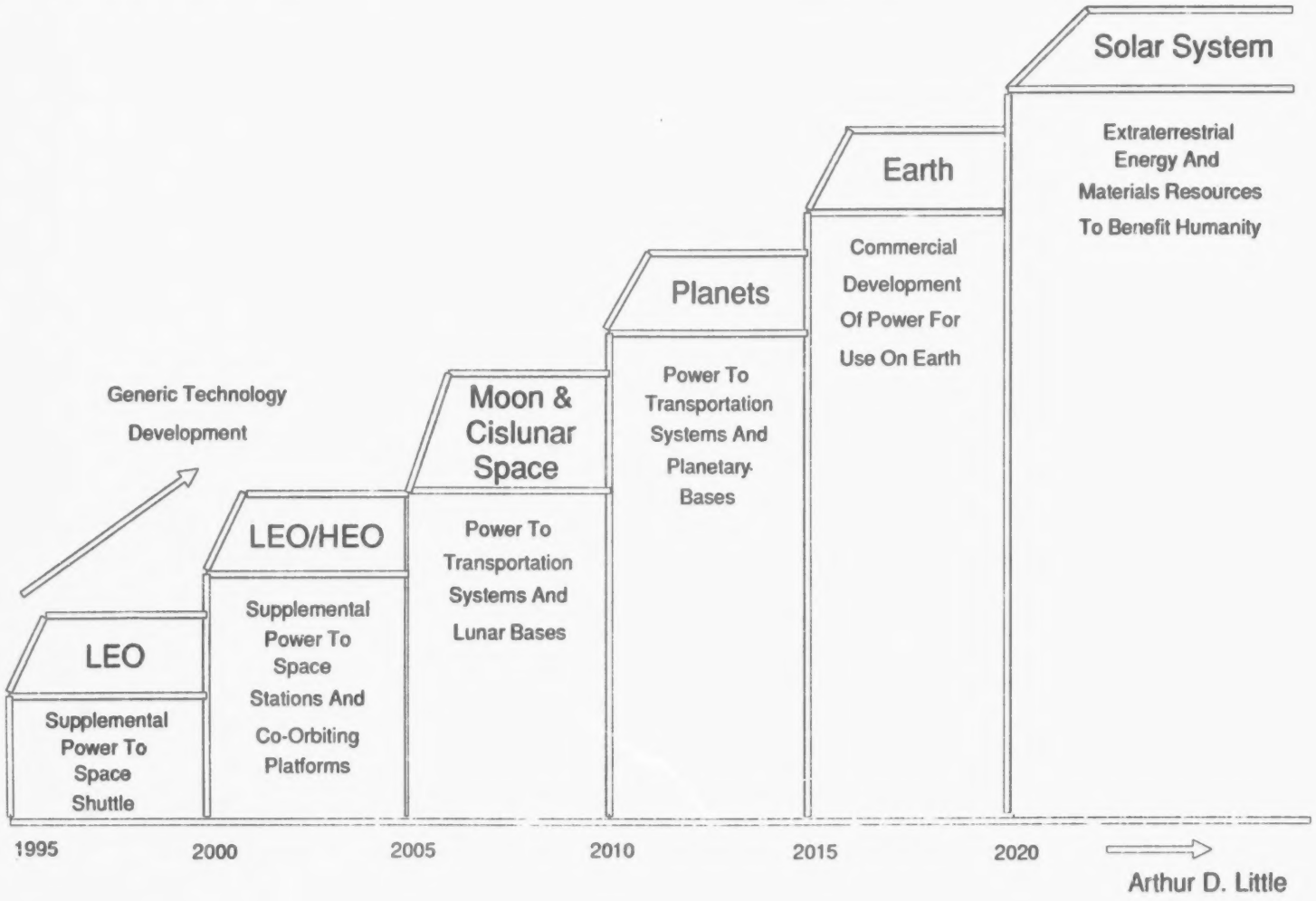

Table 1
SPS Development Goals

- o A significant contribution to meet global power demands of 25 TWyr/yr in 2030
  - 30 GW/yr
- o Microwave transmission
  - Frequency greater than 2.45 GHz
  - Efficiency greater than 70%
- o Laser transmission
  - Efficiency greater than 50%
- o Solar energy conversion with an efficiency greater than 35%:
  - Multijunction solar cells
  - Solar dynamic cycles
  - Thin Film solar concentrators
- o Structures
  - Advanced low-mass composites
  - Use of lunar resources
- o SPS mass
  - 2000 t/GW
- o Transportation
  - From Earth to GEO: $50/kg
  - From Moon to GEO: $20/kg
- o Space infrastructure: Earth to GEO
  - LEO assembly of components
  - GEO construction base
- o Space infrastructure: Moon to Earth
  - L_2 assembly of components
  - GEO construction base
  - Lunar base
- o Cost of operational SPS
  - $5000/kW ($1989) for SPS produced from lunar resources
- o Environmental Impacts
  - Within required terrestrial constraints
  - Effluents from Earth to GEO reduced through use of lunar resources for commodity materials

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LUNAR POWER SYSTEM
SUMMARY OF STUDIES FOR THE LUNAR ENTERPRISE TASK FORCE
NASA - OFFICE OF EXPLORATION

Dr. David R. Criswell*

1 INTRODUCTION

The capacity of global power systems must be increased by a factor of ten to provide 20,000 GW of electric power by the year 2050 to support the needs of 10 billion people at 2 kWe/person. Solar power bases can be expeditiously constructed on the moon to supply the majority of the needed power (Waldron and Criswell 1985, 1989).

The Lunar Power System (LPS) would collect solar energy at power bases (1 & 2, figure 1) located on opposing limbs of the moon as seen from Earth. Each base would contain tens of thousands of individual systems, each consisting of solar converters and microwave transmitters that transform the solar power to microwaves. Hundreds to thousands of low-intensity microwave beams will be directed from each base to rectifying-antenna (rectennas) on Earth (4 & 5, figure 1) and in space (8) that convert the microwaves back to electrical power. Additional sunlight can be reflected by mirrors (3) in orbit about the moon to bases #1 and #2 during lunar night. Microwave reflectors (6) in mid-altitude, high-inclination orbits about Earth can redirect microwave beams to rectennas that can not directly view the moon. The sunlight and microwave reflectors can eliminate the need for power storage on the moon or Earth, permit the LPS to follow the power output needs of each receiver, and minimize the need for long-distance power transmission lines on Earth. The complete LPS consists of the power bases (1 & 2), orbital mirrors (3 & 6), and rectennas (4, 5 & 7). Space rectennas (8) can have a low mass per unit of received power (< 1 Kg/Kw) and can enable high performance electric-rockets and rugged facilities.

LPS can provided dependable, economic, renewable, and environmentally benign solar energy to Earth. LPS requires far less equipment, land area, people, and net investment to construct and maintain than any of the other options for planetary-scale power systems. A vigorous Apollo-like program could start the construction of LPS on the moon early in the 21st Century (Mueller 1984) and thereby build on the United States journeys to the moon (Aldren & McConnell 1989).

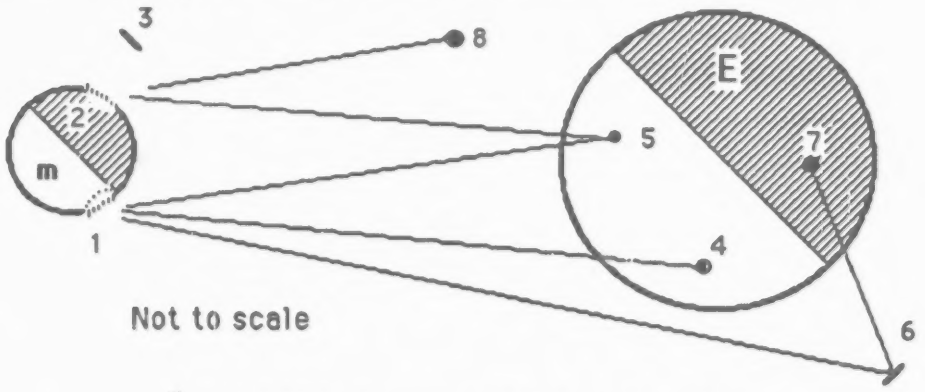

Figure1 Major Components of the Lunar Power System

A preliminary engineering and cash flow model of the LPS has been developed. Results are shown for a system scaled to a peak capacity of 355 GWe on Earth and to provide 13,600 GWe-Yrs of energy over a 70-year life-cycle of construction and full operation. This is approximately the level of electric power now required by the United States and the total quantity of electric energy consumed by the United States since the start of the electric industry in the 1880s.

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Figure 2 shows the growth in capacity of the reference system from start of installation on the moon in 2005 to completion of its nominal life-cycle in the year 2070. The Lunar Enterprise Study assumes the average price of electric power will be 0.25$/kW-Hr in the 21st Century. However, a selling price of 0.1 $/kW-Hr is assumed in the LPS reference model. This yields a net revenue for the mature LPS of approximately 300 B$/Yr. The Reference model projects operating costs of the reference LPS to be approximately 5 B$/Yr or 1/60th of revenue. Due to the low projected operating costs the LPS profit is roboust aginst increases in near-term inflation and maintenance, especially with advances in tne technology of LPS components. Total life-cycle costs would be approximately 560 B$.

Government development of the transportation system and space facilities to establish a small scientific research facility on the moon could reduce the life-cycle-costs by approximately 125 B$ and cover the initial R&D expenditures for a manned return to the moon. Government development of the initial base is likely to be essential. The initial lunar base would be extremely difficult to organize and finance privately.

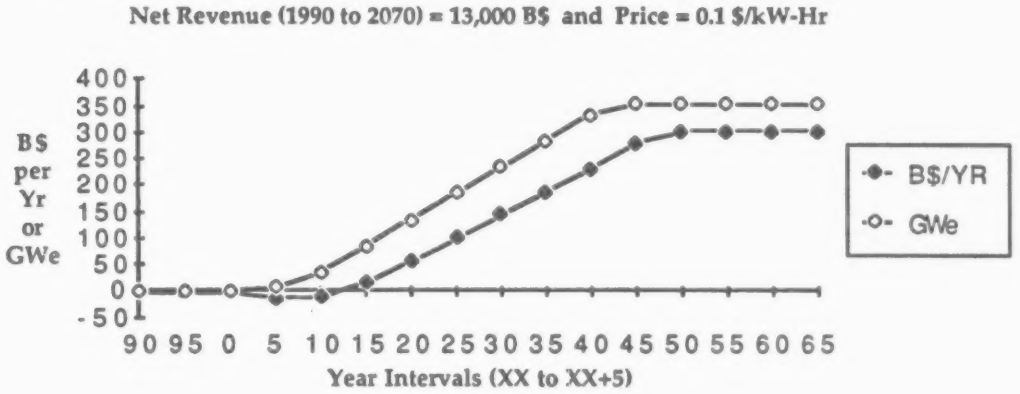

Figure 2 LPS Capacity and Revenue

World needs for power could be accommodated by expansion in capacity of the reference LPS beyond 355 GWe. This would be done by steadily incorporating newer technology during full operation and by establishing additional bases. The major expenditures are for expansion in size and power capacity of the receivers (rectennas) on Earth. Most of those costs can be paid for through local sale of power. Each receiver can operate while undergoing expansion beyond 10s MWe output. For a world demand of 20,000 GWe and a price of 0.1$/kW-Hr, power sales could approach 15,000 B$/Yr by Y2050.

2 LUNAR POWER SYSTEM

As envisioned, the mature LPS consists of several bases on the moon. Figure 3 is a montage of one concept for a demonstration LPS (lower half) and the beaming of power from mature LPS bases to Earth (upper half, scale and perspective both distorted). Bases near sunrise or sunset are illuminated by orbital mirrors such depicted on the middle right.

The dominant features of a lunar base are the plots of photovoltaic converters placed directly on the lunar surface and the large number of objects that look like billboards placed at the end of each plot. In the foreground, one small power plot is under construction. The plot consists of a relatively small area of photovoltaic cells that are made from lunar materials. See Hanak et al. (1986) and Hubbard (1989) for reviews of relevant solar cell technologies. The moon is a far better location for intrusive, large-area solar collectors (SC) than is Earth. There, sunlight is completely dependable and more intense. Compared to collectors on Earth, the lunar collectors can:

- have <0.1% the mass per unit area and therefore ultimately be produced faster because the lunar materials and environment are uniquely suitable to the production and emplacement of large area and thin film, solid state devices;

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- have far longer life because of the lack of air, water, and disturbances; and
- be immune to the environmental variations and catastrophes (e.g., weather and earthquakes) of Earth.

Most of the components of each plot can be formed of local lunar materials. Initially only 0.1 tonne (T=1 E 3 kg) of components and consumables will be required from Earth to emplace one megawatt of received power on Earth. No component imports may be required as industrial experience is acquired on the moon or with further creative research on Earth preceding a return to the moon. Very likely the majority of the mass of emplacement equipment and supplies could eventually be derived from lunar resources.

The photovoltaic cells in each power plot feed electric power to sets of solid state MMIC (monolithic microwave integrated circuits; Abita 1988) transmitters at the end of each plot. Each set of MMICs projects many individual sub-beams of microwave power at their "billboard-like" reflector on the anti-Earthward end of their plot. Every sub-beam is reflected backward toward Earth. Subsets of sub-beams from every reflector are mutually phased to form one power beam directed toward Earth.

Each "billboard" is constructed of foamed or tubular glass beams that support a microwave reflective surface consisting of a cross grid of glass fibers coated with a metal such as aluminum or iron. The billboards of one LPS base are arranged over an area near the limb of the moon so that when viewed from Earth they appear to merge, through foreshortening, into a single large synthetic aperture of diameter "l" kilometers. The local subunits of this microwave phased array of sub-arrays is distributed over zones 1 & 2 (figure 1; zone length= l = 30 km to 100 km and wavelength= w = 10 cm; $l/w > 10^6$). Each zone projects 100s to 1000s of tightly collimated power beams (<MWe to many GWe). The beams are convergent (near field), but slightly defocused, like a spotlight, to distances (= l*l/w) many times that of the Earth-moon distance. Power is combined in free space in the electromagnetic field of the transmitted beams rather than in large physical conductors as occurs in most power systems. The enormous composite antennas are possible because the moon is extremely rigid and non-seismic, there are no external disturbances, and antenna construction requires only modest amounts of local materials.

Each LPS beam can be fully controlled in intensity across its cross-sectional area to a scale of a few 100 meters at Earth. This allows the LPS beams to uniformly illuminate rectennas on Earth that are larger than 200-300 meters across. The microwave beams projected by the LPS should have very low sidelobe intensity and not have grating lobes. The stray power level should be very low and incoherent. LPS could probably operate economically at a lower power density (~ 1 milliwatt/cm^2) than the leakage allowed under Federal Guidelines (5 mW/cm^2) from microwave ovens used in homes. A beam intensity of 23 mW/cm^2, which produces little sensible heating in animals, will allow delivery of power at costs lower than those now associated with established hydroelectric dams.

It may be possible to make the stray, incoherent power levels on Earth of a 20,000 GWe LPS less than a human, or the Earth, radiates thermally in the microwave. If so, the power-beaming system can be completely safe.

LPS beams can efficiently service rectennas on Earth once they are more than 200 meters in diameter and several 10s of megawatts in power output. Thus, as rectennas are enlarged beyond a diameter of 200 meters, the additional growth can be paid for out of present cash flow derived from power sales.

A given lunar base is adequately illuminated only 13.25 of the 29.5 days of the lunar month. Several complementary methods are available to provide a steady stream of power to users on Earth. Pairs of bases built on opposite limbs of the moon could supply power for 26.5 out of 29.5 days of the lunar month. Favorable siting of the bases on slopes in the limb regions of the moon may also decrease the period of lunar dusk below three days. Approximately three days of power storage could be provided at each plot of a lunar power base to ensure an uninterrupted flow of power. Or, power storage can be provided on Earth and the LPS system scaled up to provide the additional three days of power every 29.5 days. However, with present technology, power storage is very expensive. Even with pumped hydro-storage on Earth using one surface and one deep (1 Km) reservoir, the storage of 300 GWe of power for three days would exceed all other costs. The preferred solution is to keep the lunar bases illuminated and delivering power continuously. Large mirrors, "lunettas," can be placed in orbit about the moon and oriented to reflect sunlight to the bases.

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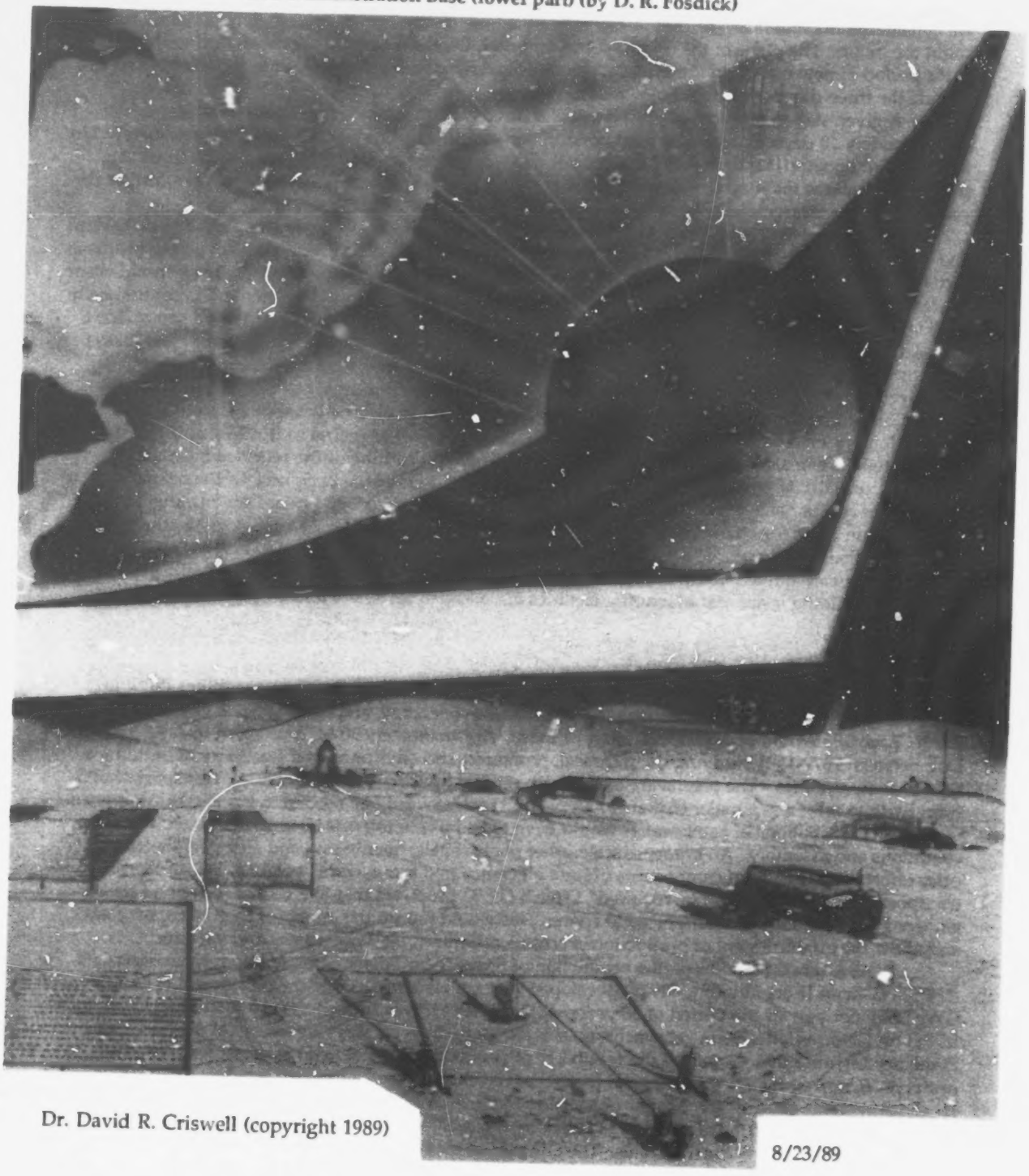
Figure 3 Montage: Beaming power from moon to Earth (top part, not to scale) and LPS Demonstration Base (lower part) (by D. R. Fosdick)



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Lunettas, a version of solar sails (Garvey and Adkisson 1988, Criswell 1979), can have a low mass per unit area, be of low optical quality (no convergence), and be constructed primarily of glass fibers and trusses and a thin film of reflective metal such as aluminum. The masses and costs of lunettas are considered in section 3. The estimates assume the lunettas are evenly spaced along a polar orbit about the moon. The plane of the orbit is coincident with the terminator of the moon during the middle of the period of new moon. In the model no credit is taken for sunlight delivered to the solar converters outside the three-day period about new moon.

A given station on Earth can receive power directly from the moon when the moon is approximately 10 degrees above its local horizon and over a daily angular sweep of approximately 120 degrees. For equatorial stations the lunar power beam could be received for one-third the time. At poleward locations the moon would be sufficiently high above the local horizon about one-third of the year. Most power usage on Earth occurs between 30 and 60 degrees of latitude.

The final space components of the LPS are microwave mirrors (MM) in low altitude (<5,000 km) and high inclination (30 to 90 degree) orbits about Earth. They can economically reflect power beams to rectennas that are blocked by Earth or attenuated by long paths through the atmosphere as would occur for rectennas at high latitudes. Each MM is approximately 1 kilometer in diameter and is continuously reoriented to reflect a microwave beam from the moon to a rectenna on Earth. The MMs also provide a means for multiple power beams to be delivered to a given rectenna. The MMs have a very low mass per unit area and per unit of reflected power. The major components are a rigid frame, a microwave reflective grid of fibers held in place by the frame, and an orientation system. Drag make-up and orientation can be supplied by ion-thrusters that are powered by electricity tapped from the reflected beam. Momentum control devices (momentum wheels or moment-of-inertia controllers) and gravity gradient tethers can also be used for attitude control. The fine pointing of the reflected beam can be done electronically at the moon by shifting between transmitters at the periphery of the beam.

MM components would be made on Earth and assembled in orbit. Little if any mass will be required from Earth for operation of the MMs. An MM would have approximately 1/300th the mass per kW of "handled" power of a Space Solar Power Satellite (SPS; Glaser 1977; NRC 1981). The costs of these reflectors are not explicitly calculated in the LPS model but are included in a 10% allowance of the costs of building space manufacturing facilities discussed in sections 3 and 4.

3 MODEL

P. Glaser (1977) introduced the concept of establishing huge solar power satellites (SPS) in space that could collect solar power, convert it to microwave energy, and beam the power to rectennas on Earth. Each SPS would operate for 30 years or more. Approximately 30 M$ was spent by NASA and DoE between 1977-1981 studying the technical, economic, and environmental feasibility of building a fleet of such satellites. The results are extensively reported (OTA 1981, NRC 1981). Transport of SPS from Earth to orbit was a major challenge. Very large rockets would be needed to launch the components into space. The billions of components would have to be built to tolerate terrestrial, launch, and space conditions and assembly. An immense scale-up of photovoltaic, microwave, and space engineering over prior efforts and the use of components of high efficiency and low specific weight to off-set high transport costs to orbit would be required. O'Neill (1975) proposed that SPS be built out of materials gathered on the moon and transported to space. This would reduce the impact of high transport costs and allow the establishment of production processes optimized for zero-gravity and vacuum.

NASA funded studies on the production of Space Solar Power Satellites from lunar materials (LSPS). General Dynamics (Bock 1979) developed systems level models for the production of one 10 GWe LSPS per year over a period of 30 years. MIT (Miller 1979) examined the production and design of LSPS and factories for LSPS in geosynchronous orbit. Both drew on previous studies at the Lunar and Planetary Institute that examined the feasibility of producing engineering materials from lunar resources (Criswell 1980, 1979). General Dynamics (GD) formulated a system level infrastructure model for the systematic analysis three lunar production options. A NASA reference model for a 10 GWe SPS to be deployed from Earth was used to establishing the performance requirements (JSC 1978) and reference costs (JSC 1977) for the LSPSs. The GD studies explicitly included estimates of costs of research and development, deployment, and operation of a fleet of 30 LSPS. Case D of the GD study

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assumed extensive production of chemical propellants (Al and O2) and LSPS components on the moon. Case D is similar in type and mass of equipment and the number of people off Earth to an LPS system with the capacity to emplace approximately 30 MWe(=MWs received at earth) of power every 24 hours. General Dynamics estimated the total program costs to be 620 B$ for LSPS Case D.

A spread sheet model based on the GD results was developed for the mass of equipment and components, number of people, and costs of establishing a Lunar Power System of arbitrary size (Criswell 1989 a, b & c). The LPS model includes the major materials-handling and production operations on the moon and in orbit about the moon. These are: smoothing the soil and forming the north-south ridges; beneficiating iron from the soil; producing dense and foamed glass components for stabilizing ridges, forming frames of microwave reflectors, and producing the glass (metal-coated) fiber grid stretched across the frames; producing amorphous silicon solar cells, producing most of the microwave production system, shipping mirror material from the moon to lunar orbit, and producing mirrors in lunar orbit. Table 1 gives the key parameters.

Table1 Major Parameters for Modeling LPS Production and Operation

	LPS TECHNOLOGY LEVEL	
Engineering Factors	Reference(1980s)	Advanced(2000s)
LPS System Factors		
Electric to microwave conver. eff.	0.4	0.9
Solar Cell Efficiency	0.1	0.35
Mass of orbital mirrors (T/Km**2)	10	3
Solar exposure per day	1/Pi	1
Wavelength of power beam (cm)	10	2
Diffract. beam width Earth (Km)	0.5	0.2
Productivity Factors		
Equip. work hours per 24 hours	12	23
Beneficiation equip.(T/T/Hr)	1	0.01
Excavation equipment (T/T/Hr)	0.1	0.01
Hot forming equip. (T/T/Hr)	10	.03
Terrestrial components (T/MWe)	0.1	0.01
Habitat mass per person	5	1
Constant or Minor Adjustment*		
Free iron in soil (weight fraction)	0.001	0.001
Weight fraction adhered glass	1	1
Height of solar cell supports (m)	0.3	0.3
Thickness reflector frames(m)	0.2	0.2
Electric collection efficiency*	0.9	0.99
Assembly of macro-parts (T/T/Hr)	100	100
Micro-parts production (T/T/Hr)	3000	3000
Chemical refining (T/T/Hr)	100	100
Electric mass driver (T/T/Hr)	500	500
System availability*	0.9	0.99
Rectenna collection efficiency*	0.95	0.98
Beam inten. rectenna (mW/cm**2)	23	23
Growth, Costs, & Sales	**Ref.**	**Range**
Growth rate (GWe/Yr/Yr)	1	0 & 1
Steady production (GWe/Yr)	10	1 to 100
Period steady construction (Yrs)	30	1 to 100
Installed capacity (GWe)	355	1 to 10,000
Near-term inflation (1990$/1977$)	1.7	1 to 80
Maintenance factor	0.5	0 to 90
Price of electric power ($/kWe-Hr)	0.1	0.005 to 0.3

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4 Results

The model was exercised over a wide range of the parameters listed in Table 1. The two sets of parameters selected were judged to represent levels of technology corresponding both to the 1980s time frame (Reference) and the level of advanced technology that is expected to be available in the year 2000.

Table 2 presents the results for both sets of assumptions applied to the construction of 27.3 MWe/24 hours or 10 GWe/Yr over a 30 year period, approximately 2005 to 2035. The General Dynamics study was done assuming 1977 dollars. Table 2 makes no adjustment for inflation between 1977 and 1989.

TABLE 2 Reference & Advanced

ITEM	TECHNOLOGY LEVEL	
	Reference(1980s)	Advanced(2000)
Sunlight to Earth Power	0.01	0.20
Materials mined (T/Yr)		
Scraping	160,000,000	8,000,000
Beneficiation	35,000,000	7,900,000
Others (glass, iron,...)	2,040,000	1,970,000
Equipment on Moon (T)		
Mining	11,600	52
Processing	33,000	4,100
Support & habitats	3,900	140
Space Facilities (T)		
Low Earth Orbit	20,000	2,000
Low Lunar Orbit	3,000	300
Materials to Space (T/Yr)		
Moon to LEO	90,000	16,627
Earth to Moon	5,400	400
People		
Moon	500	50
Low Lunar Orbit	100	10
Low Earth Orbit	50	5
Total Costs(B$)	320	140
R&D, Production, & Space Operations B$	220	40
Rectennas on Earth B$	100	100
Power Costs ($/kWe-Hr)	**0.009**	**0.004**
Earth Mass(T) shipped to moon (T/GWe-Yrs)	**20**	**1.5**

Technology advancement decreases both the area of the lunar surface and of mirrors in orbit about the moon that are necessary to capture and transmit a unit of solar power. This greatly reduces the size of machinery and number of people necessary to install and maintain the bases. A scientific lunar base would require approximately the same scale of transportation as an advanced LPS (Lovelace et. al. 1989).

Cost of power is projected to be low in both cases, 0.9 and 0.4 ¢/kW-Hr. The cost of power from the Advanced System does not drop further because no technology advancement is assumed for the rectennas on Earth. Lower costs rectennas may be possible. Neither the time value of money, except as allowed for in the General Dynamics study, nor regulatory expenses or taxes are included in the costs.

The General Dynamics study estimated the expenditures (1977$) for research and development (R&D), production, and maintenance of all elements of the LSPS and the production system. A total expenditure was presented for each item of the infrastructure analysis. A 1990 - 2070 life-cycle model was produced for the LPS by distributing each of the LPS expenditures derived from the General Dynamics model over their relevant portion of LPS life cycle. For example, rectenna R&D was taken to be 1% of the total expenditure on rectennas and was spread evenly over the 1990 - 2005 period. R&D for space transportation was concentrated in the 1990 -2000 time frame and production in the 2000 - 2005

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period just before a return to the moon.

Figure 4 depicts the projected expenditures for the 1980's technology case. The expenditures are separated into space elements of the Lunar Power System (LPS), the rectennas on Earth (RECTN), all aspects of the space transportation system (Trnsp. - rockets, propellant depots, facilities on Earth), and the Lunar Base (LunB). Research and development is concentrated in the 1990 to 2000 time frame, production of space transportation elements, lunar and space habitats, and emplacement machinery in 2000-2005 and their deployment and initial operation in 2005 - 2010. The federally funded scientific lunar base is completely installed in 2005. Beginning in 2005 the lunar base expenditures (LunB) include only purchases of power and services at a rate of 75$/kW-Hr and for a quantity of power that increases from 25kW in 2005 to 4.2 MW in 2015. In 2015 the price of power to the lunar base decreases to 0.1 $/kW-Hr and becomes insignificant. The majority of the power is embedded in lunar-derived propellants and materials to support operations of the scientific lunar base.

Emplacement of the LPS on the moon begins in 2005 at the rate of 1 GWe/Yr and the installation capacity is increased every year by 1 GWe/Yr from 2005 through 2015. After 2005 the LPS section includes both the habitats and emplacement machinery. The expenditures in Figure 4 assume the Federal government does the R&D for the establishment of a lunar base and the associated transportation system. Thus, the LunB and Trnsp. items between 1990 and 2005 are Federal expenditures. The organization that establishes the lunar power system pays for LPS and RECTN items between 1990 and 2005 and after 2005 it also pays for all transportation and manned production activities on and off the moon. Rectennas expenditures are primarily for R&D during the 1990 - 2005 period. Rectenna expenditures increase sharply in 2005-2010 as construction of demonstration antennas begins. Power begins to be received from the moon in the latter part of 2005 and revenue begins to grow quickly.

Advances in technology can sharply decrease expenditures during all phases of the LPS program. Factors of 2 to ten decrease in annual cash flow can result for the Transportation, Lunar Base and LPS categories. Rectenna construction is assumed to remain unchanged.

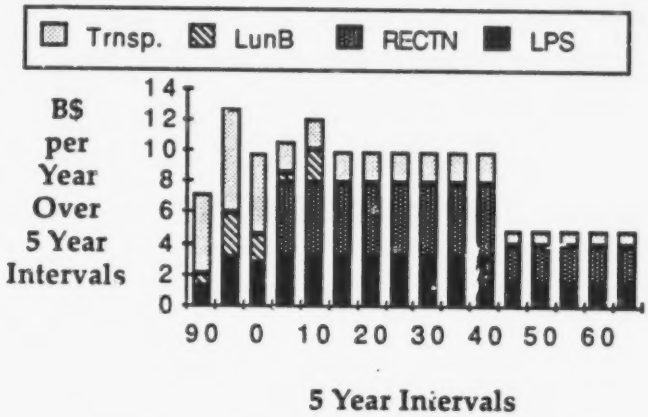

Figure 4 LPS Expenditures for Reference System

Analyses by other reseachers will differ, especially of costs for such a large and complex project over 85 years. To encourage more research, the models were run to determine the ranges of near-term inflation (1990$/1977$) and maintenance for which the LPS would provide a cumulative net revenue that was positive (B$ net at Y2070). Figure 5 shows the effects of near-term inflation. Near-term inflation can be taken as an actual correction for inflation between 1977 and the start of the project or as a multiplier to all the costs of establishing and maintaining the LPS. Thus, zero inflation corresponds to an LPS that costs nothing to build or operate. An inflation of "one" means the cost of money is the same as in 1977 over the life of the project.

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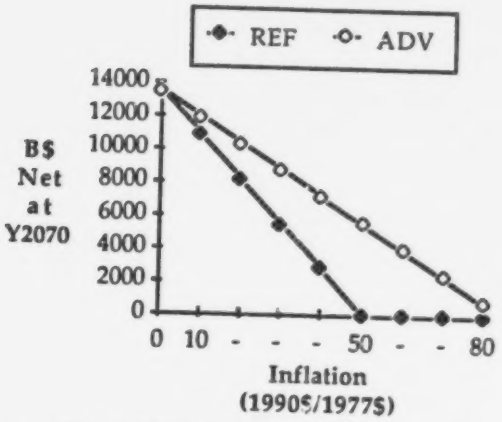

Figure 5 Net profit versus inflation

Figure 5 assumes that power is sold at an average price of 0.1 $/kW-Hr and that maintenance is conducted at a high enough level to rebuild 50% of the lunar and space installations over the last 25 years of operation. Figure 5 reveals that the costs presented in Table 2 must increase for the 1980s case by a factor of 50 (5000%) before the net revenue goes to zero. For the case of advanced technology the inflation must increase by a factor of 83 (8300%).

Figure 6 shows the results of similar calculations in which the inflation is held constant at 1.7 and the maintenance factor is changed. A maintenance factor of 1, or 100%, corresponds to rebuilding the lunar and terrestrial components once over the last 25 years of operation. For the REF case (1980s technology) the maintenance must increase by a factor of 55 and by 110 for the ADV case before the cumulative revenue at 2070 goes to zero.

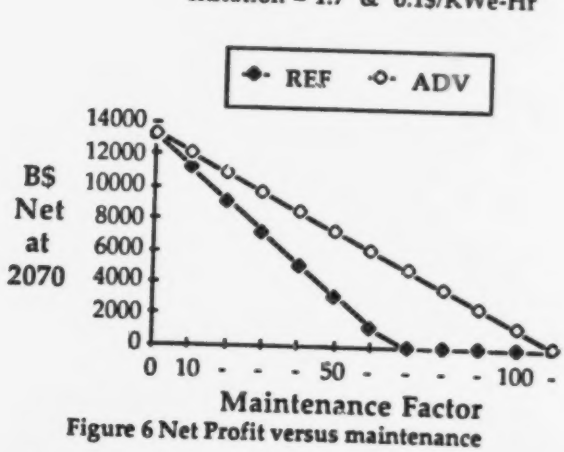

Figure 6 Net Profit versus maintenance

The inflation and maintenance calculations indicate that the net revenue of the LPS will be positive in the face of major increases in construction and maintenance expense. Technology advancement should strongly increase the probability that LPS will provide net positive returns at a price of electric power competitive with prices today. If the average selling price of electricity increases above 0.1 $/kW-Hr then the LPS becomes even more viable. Figures 5 and 6 make it clear that

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LPS provides an unusually robust concept for the acquisition and delivery of power that should receive additional analysis.

5 GLOBAL POWER SYSTEMS

Table 3 provides a high-level summary of the scale of equipment and consumables that must be organized and used to support various types of 300 GW power systems based in space (Space Systems) and on Earth (Terrestrial Systems) over a 70 year life-cycle. The LPS and SPS avoid the burning of both fossil and radioactive fuels within the biosphere. In addition, but not included here, the LPS and SPS systems can redirect power about the world without the use of power lines or the shipping of fuels. "Total Equip." refers to the total mass of machinery, habitats, components, and equipment that must be shipped to space from the Earth over the 70 years of power production. Thus, the smaller the "Total Equip." the smaller the overall mass of launch and production equipment required on Earth. Small values of "Specific Mass" are preferred. Neither include the mass of rockets or propellant.

Table 3 Scale of 300 GW Power Systems Over 70 Years & Gross Energy Produced Over 70 Years

SPACE SYSTEM (Mass from Earth)	First Year Equip. (T)	Total Equip. (T)	Total Energy (GWe-Yr)	Specific Mass (T/GWe-Yr)
Advanced LPS	**500**	**20,000**	**13,620**	**1.5**
He3 (fused on Earth)	2,000	90,000	10,200	10
Reference LPS	6,000	280,000	13,620	20
Advanced SPS (~1 T/MWe)	2,000	400,000	9,300	40
Lunar-derived SPS (GD study) with these transport means off the moon				
.....lunar Al fuel & LO2	300,000	700,000	9,300	80
Earth SPS (NASA Ref., 10 T/MWe)	30,000	4,500,000	9,300	500

TERRESTRIAL SYSTEMS	Fuel(70 Yrs) (T)	Equip & Plant(T)	Tot Energy (GWe-Yrs)	Specific Mass (T/GWe-Yr)
SPS Rectenna Pedestals	-	6 E 7	(13,650)	4,000
(Electrical elements*2)	-	(3 E 5)	(13,650)	(20)
Coal Plants, Mines, & Trains	4 E 10	9 E 7	9,000	10,000
Nuclear fission	1. E 5	3 E 8	9,300	30,000
Hydro* & TSP (w/out storage)	*1.4 E 15	1.2 E 9	13,650	900,000

( ) - Counted in preceding row

Both the LPS and SPS require rectennas on Earth. Their mass is shown in Terrestrial Systems. Note that E "X" means 10 to the Xth power. Rectenna mass is dominated by simple pedestals that support the receiving antennas. This estimate assumes the pedestals are made of concrete. The LPS rectenna should have a pedestal mass that is 1/2 or less that of the reference SPS. Only 5,000 T of electrically active elements of are required in a 10 GWe rectenna. The rectennas are much less massive structures and simpler systems than those associated with coal, nuclear, hydroelectric, or terrestrial solar power facilities (TSP). The TSP do not store power.

Another option is to obtain from the moon the He3 present in the soil at a weight fraction of 5 E-9. Theoretical models indicated that He3 fusion reactors might be approximately the same mass as present fission reactors of equal power capacity (NASA 1988). Fusion of deuterium (D) and He3 induces far less radioactivity than does fusion of D and tritium (T). Fusion R&D programs must be reoriented and expanded to enable the production of commercial He3 fusion reactors by the 2020s.

A 300 GWe nuclear fission system would consume approximately 350 T/yr of uranium. Operational nuclear plants convert only 2% of their nuclear fuel into energy; thus, the order of 17,000 T/yr of nuclear fuels must be recovered, reprocessed, and transported (Cohen 1980).

Remember that Table 3 applies to the production of only 9,300 to 13,620 GWe over the 70 year life-cycle of the various power systems and a peak capacity of 300 to 355 GWe for the last 25 to 40 years. Human needs must be considered on a global scale (Criswell 1985). A world-wide system for

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supporting 20,000 GWe would require approximately 70 times more equipment and consumables every 70 years. In the case of coal this would imply the consumption of 40 E 9 T/Yr. At present, world industrial consumption of carbon is 5 E 9 T/Yr, and the net increase in atmospheric carbon is 3 E 9 T/Yr. Also, all the world's living plants only convert 50 E 9 T/Yr of atmospheric CO2 back into burnable carbon (Houghton and Woodwell 1989). Neither coal nor renewable plants can support the production of 20,000 GWe. World agricultural needs, pollution control, pollution, greatly increasing atmospheric CO2 (which drives the green-house effect), and increasing competition for fossil fuel will sharply drive up energy costs.

A nuclear electric economy requires the breeding of fissile fuels. A 20,000 GWe nuclear power system would be approximately 500 times larger than the nuclear industry which now meets 15% of the world's electrical needs (Foley 1987). Proliferation of weapons-grade materials and disposal of spent fuels and the contaminated plants would be a rapidly growing and long-term problem (100s to 100,000s years).

The world hydroelectric resource (> 5 MWe installations) is estimated to be only 2,200 GWe and by 1983 20% was harnessed (Twidell and Weir 1986). Hydroelectric generation of 20,000 GWe through a 100-meter head at 50% efficiency would require the flow of 1.3 E 15 T/Yr of water. Ocean thermal plants and facilities for hydro-storage of terrestrial acquired solar energy would manipulate far greater flows of water.

6 LPS SUMMARY

Why is the LPS so attractive as a large scale power system? There are at least twenty-four fundamental reasons. The sun is a completely **dependable** fusion reactor that supplies **free** and **ashless** high-quality **energy** at high concentrations within the inner solar system, where we live. The LPS primarily handles this free solar power power in the form of photons. Photons weigh nothing and travel at the speed of light. Thus, **passive** and **low-mass equipment** (thin-films, diodes, reflectors, and antennas) can collect and channel enormous flows of energy over a **great range** to end uses as and **where** the energy is **needed** and **without physical connections**. The LPS is a **distributed** system that can be **operated continuously** while being **repaired** and **evolving**. All other power systems require massive components to contain and handle matter under intense conditions or require massive facilities to store energy. Low mass and passive equipment in space and on the moon will be **less expensive per unit of delivered energy** to make, maintain, decommission, and recycle at the end of its useful life than massive and possibly contaminated components on Earth.

The **moon** is a uniquely **suitable and available natural platform** for use as a power station. It has the right materials, environment, mechanical stability, and orientation and remoteness with respect to Earth. The major non-terrestrial components of LPS can be made of lunar materials and the large arrays can be sited on the moon.

The **rectennas** on Earth are simple and can be constructed as needed at **minimum up-front costs**. The LPS can be far **less intrusive**, both in the physical and electromagnetic sense, than any other large power system. Most of the power can be delivered close to where it is needed. LPS can **power its own net growth** and establish **new space** and **Earth industries**. Finally, all of this can be done with **known technologies** within the period of time that the people of Earth need a new, clean, and dependable source of power that will generate **new net wealth**.

7 PACE OF DEVELOPMENT

LPS can be developed expeditiously. Many of the key technologies for LPS are developing rapidly because of their value in the terrestrial market place. Thin-film solar arrays and MMICs are two examples. Other areas such as processing of lunar materials with minimal use of reagents and manufacturing techniques appropriate to lunar and space conditions will only be done under special funding. There will be intense interaction between LPS design and the list of key technologies in Table 1. Undoubtedly, the LPS design presented in this paper can be improved.

New vehicle concepts, such as being developed for the United States Advanced Launch System (ALS), can reduce the costs of transportation from Earth to orbit. Criswell (1989d) has presented a

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broader systems concept. It has long been known that single-stage-to-orbit (SSTO) rockets can transport modest payloads (~1% of gross vehicle weight) of fixed size from Earth to orbit. However, SSTO rockets could be linked together, provided with propellant cross-feed, and operated as parallel burn-step rockets to loft arbitrarily large payloads (internal, external cannisters/facilities, or rugged manned vehicles) to orbit (>5% of gross vehicle weight). Conceivably, one or two types of SSTO rockets could replace the present fleet of many different types of multiple-stage rockets and also perform deep space missions. Many possible advances in transportation (tethers, mass drivers, solar sails,lunar derived heat shields) can greatly increase the capacity and and improve the economics of space transportation. The United States space station program, *Freedom*, might be able to contribute habitats and production facilities for LPS.

Of course, much more extensive and refined financial and engineering analyses must be done of LPS than were possible under this study. They can be started immediately. They can draw far more deeply than did this study on the results of the 30 M$ invested in 1977-1981 NASA/DoE investigations of the SPS, the 28 B$ invested in the Apollo program, the 100 M$ invested in post-Apollo research on lunar samples and lunar geophysics, and the extensive and accelerating achievements in electronics technologies that have occurred since LPS was first conceived approximately a decade ago. All the key elements in transportation, power beaming, lunar operations, rectenna construction, microwave reflectors, and solar sails are well within the detailed expertise of the relevant technical communities. No aspects of LPS require fundamental research. Technology advancement can bring down the costs shown in Figure 4 and speed the implementation of LPS.

LPS can grow to meet the energy needs of people on Earth and establish space industry. Bases on the moon can grow to project many 10,000s GWe. The rectennas on Earth can range in size from 10 MWe to many 10s GWe. Rectenna production and operation could be done by local private or public organizations. Developing countries could install rectennas as fast as needed by the local economy. Because small rectennas would be economical it would not be necessary to build extensive high-tension transmission systems. Use of trees for fuel and of water for power production could be greatly reduced. Power from the moon could provide energy without depleting natural resources. LPS can create new wealth on Earth and eliminate major sources of pollution of the biosphere.

The results of this study encourage consideration of a faster paced program than assumed in Figures 2 and 4. After all, Apollo was done in 9 years out of a sense of fear and adventure using the limited technologies of the 1950s. To accomplish LPS the nation can now draw on far more knowledge and capabilities and know that the rewards can be great for the people of America and the world.

ENJOY!

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APPENDIX B-5

TRANSPORTATION AND OPERATIONS ASPECTS OF SPACE ENERGY SYSTEMS

Gordon R. Woodcock

The three energy systems were examined to understand the need for and importance of space transportation and operations.

Lunar Helium-3: Although the helium-3 resource on the Moon is enormous compared to its availability on Earth, it is quite rare in terms of its concentration of a few parts per billion in the lunar regolith. Consequently, the main space transportation challenge is the delivery of mining and extraction equipment. Return of extracted helium-3 to Earth is trivial by comparison. Our analysis showed that conservative extrapolations of today's space transportation systems, and use of lunar-derived hydrogen and oxygen propellants obtained as a byproduct of helium-3 production, lead to projected transport costs to the Moon below the upper economic limit of $3000/kg.

Helium-3 production is clearly the easiest of the three concepts to demonstrate (from the space transportation and operations point of view). Such demonstration, consisting of the experimental extraction of a few kg. of helium-3 over a year or more time, is compatible with the activities of an early lunar base.

Solar Power Satellite: This concept enjoys the soundest overall technical foundation. Every technical aspect of the SPS concept has been demonstrated on a practical scale; there is little doubt that an SPS, if constructed, would work, i.e., transmit useful energy to Earth. The challenge of the SPS is to produce hardware for very large space systems at costs commensurate with today's commercial industrial practice, and transport the hardware to geosynchronous orbit and assemble it there at similarly low costs. Even if most of the SPS hardware is produced on the Moon, as here proposed, the transportation rate, at least 10,000 metric tons per year to low Earth orbit, is more than an order of magnitude greater than present-day traffic (a few hundred tons per year). Relatively sophisticated transportation infrastructures are needed to obtain low-cost delivery from the Moon and from Earth and to support production operations on the Moon and assembly and checkout operations in geosynchronous orbit.

Transportation cost extrapolations, using reasonable economy-of-scale factors, project economically feasible overall transportation and operations costs for the lunar-derived SPS option.

The physics of microwave power beaming demand a relatively large-scale demonstration project. From the transportation standpoint, the demonstration is about twice as demanding in terms of total Earth launch as constructing a model lunar base: roughly 40 launches of a representative heavy-lift vehicle. A demonstrator SPS using laser power transmission could be much smaller, but with the expected relatively low efficiency of a laser power beam, would be less likely to demonstrate the potential for economic energy supply.

Lunar Power System: The space transportation and operations requirements for this energy concept are poorly understood because the concept has been less studied than the others. It is argued by the advocates that this concept can be almost entirely bootstrapped on the Moon from lunar materials. This is at least plausible, but there are important gaps in knowledge. First, the microwave power transmission performance requirements are at least an order of magnitude more severe than for the SPS, and the SPS itself requires unprecedented performance, about 20 db more gain than the Arecibo space astronomy antenna. Secondly, lunar surface operations are required on a very large scale and are very poorly understood at present. On the basis of present knowledge, the space transportation requirements for the LPS appear more modest than for SPS. However, we do not really understand the lunar surface operations requirement, and this could reverse the comparison.

It is important to recognize that if the LPS works, there is a qualitative economic difference compared to the other systems. This is that a given investment in space transportation and operations leads to a given capability for increasing the rate of power system installation, while in the case of the other systems, the investment leads to a given rate of installation.

The LPS appears to be the most difficult to demonstrate because of the physics of microwave optics and the relatively great (10 x GEO) transmission distance involved. This observation is very preliminary because our understanding of this concept is very preliminary.

PURPOSE OF ANALYSIS

A brief comparative analysis was made for three concepts of supplying large-scale electrical energy to Earth from space. The concepts were (1) mining helium-3 on the Moon and returning it to Earth; (2) constructing solar power satellites in geosynchronous orbit from lunar materials (the energy is beamed by microwave to receivers on Earth); (3) constructing power collection and beaming systems on the Moon itself and transmitting the energy to Earth by microwave. This analysis concerned mainly space transportation and operations, but each of the systems is briefly characterized in the following material to provide a basis for space transportation and operations analysis.

Purpose of Analysis

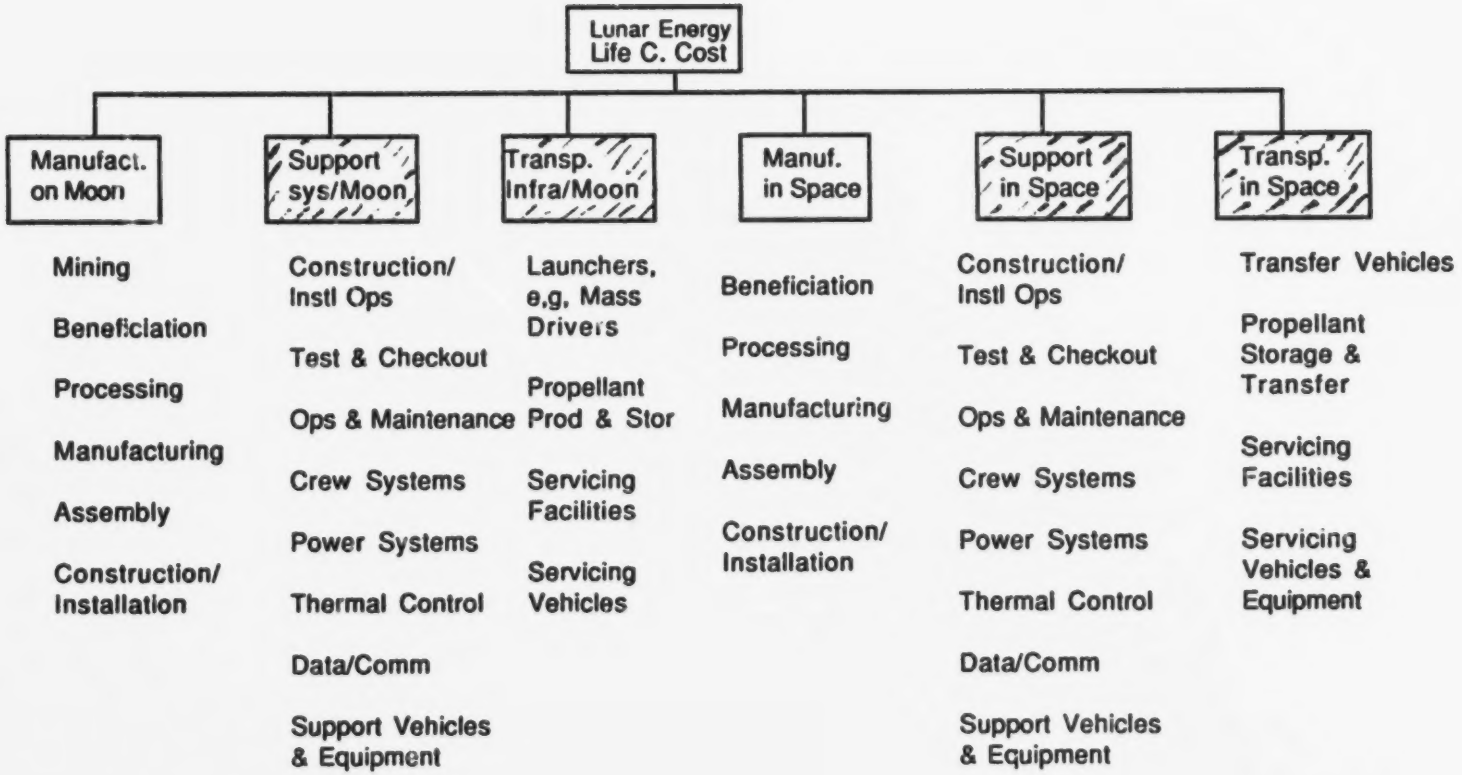
Roughly Normalize the Space Transportation and Operations Requirements of the Three Energy Options.

Develop Rough-order-of-magnitude Transportation and Operations Costs.

Compare the Demonstration Requirements of the Three Options re Space Transportation and Operations.

Lunar Energy Life Cycle Cost Work Breakdown Structure

The facing page illustrates a complete work breakdown structure for the space segments of lunar energy systems. This study concerned portions of the shaded elements.


Lunar Energy Life C. Cost
Manufact. on Moon
Support sys/Moon
Transp. Infra/Moon
Manuf. in Space
Support in Space
Transp. in Space
Mining
Beneficiation
Processing
Manufacturing
Assembly
Construction/ Installation
Construction/ Instl Ops
Test & Checkout
Ops & Maintenance
Crew Systems
Power Systems
Thermal Control
Data/Comm
Support Vehicles & Equipment
Launchers, e.g, Mass Drivers
Propellant Prod & Stor
Servicing Facilities
Servicing Vehicles
Beneficiation
Processing
Manufacturing
Assembly
Construction/ Installation
Construction/ Instl Ops
Test & Checkout
Ops & Maintenance
Crew Systems
Power Systems
Thermal Control
Data/Comm
Support Vehicles & Equipment
Transfer Vehicles
Propellant Storage & Transfer
Servicing Facilities
Servicing Vehicles & Equipment

Lunar Helium-3 Concept

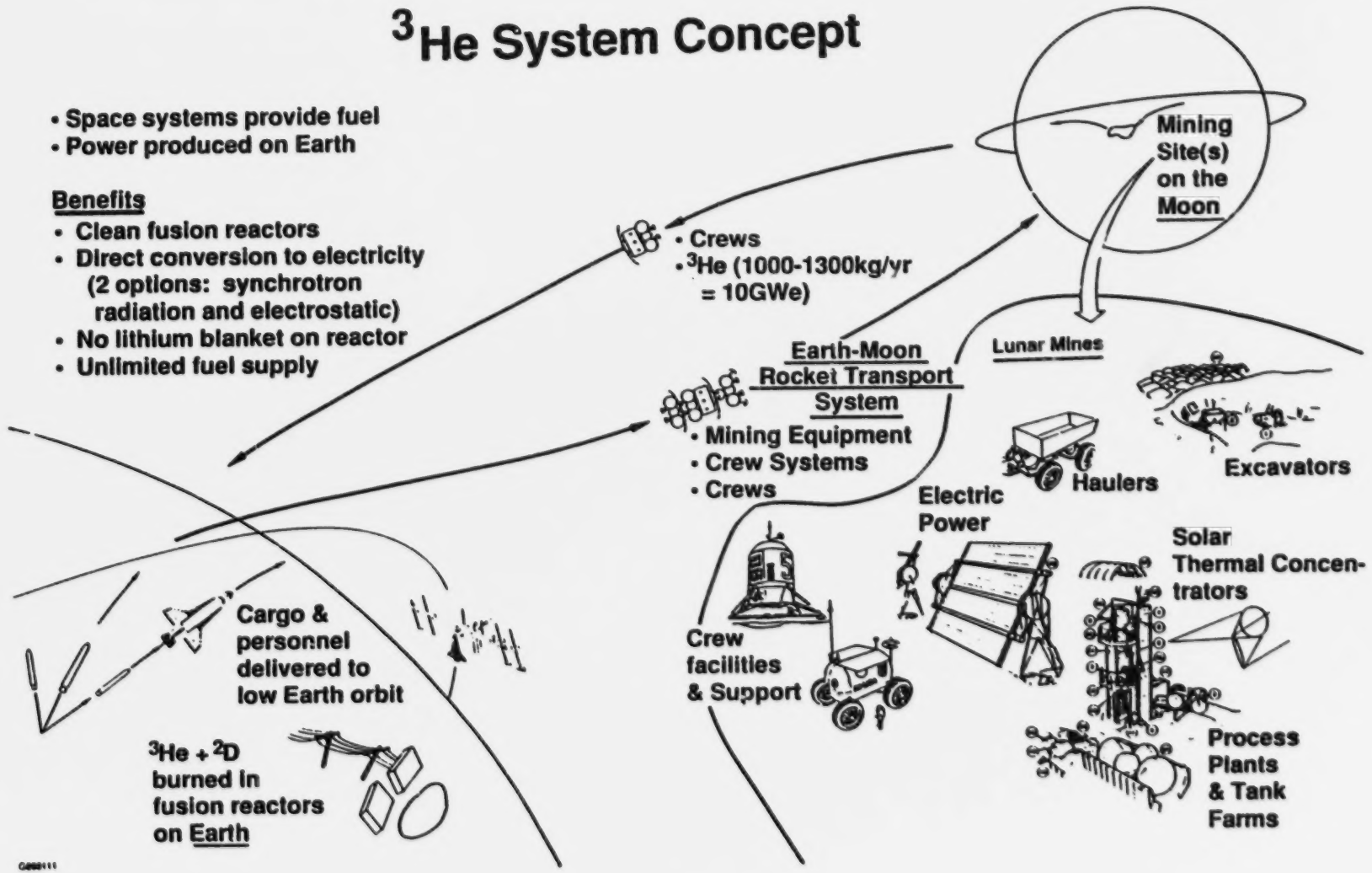
The approach to acquisition of helium-3 from the Moon is diagrammed here. The principal space transportation and operations requirement is to deliver, set up, and operate the extraction systems (mining, beneficiation, volatiles extraction, helium-3 separation) on the Moon. Regolith is mined, beneficiated to select the grain size range most productive of volatiles, and heated to drive off the volatiles. Process heat will be derived from solar conentration; other process energy will be electrical. Beneficiation and volatile extraction may be done locally by the mining machines, or in a central processing plant, or partly by each. Volatiles other than helium-3 will be separated and stored for industrial use, e.g. as rocket propellant. Separated helium-3 can be returned to Earth on crew return flights. One metric ton per year of helium-3 will generate 10,000 megawatts of electricity continuously.

^{3}He System Concept

- Space systems provide fuel
- Power produced on Earth

Benefits

- Clean fusion reactors
- Direct conversion to electricity (2 options: synchrotron radiation and electrostatic)
- No lithium blanket on reactor
- Unlimited fuel supply



Helium-3 System Sizing

All of the systems were sized at an energy production rate of 10,000 megawatts (10GW) net delivered on Earth for comparison purposes. This does not imply that 10 GW is an appropriate size for a generating system; indeed these systems have significant differences in unit size capability.

The quantity of helium-3 required is a straightforward energy calculation. The key is that one atom of helium-3 (3 amu), reacting with a deuterium atom, releases 18.3 MeV of energy. 50% conversion efficiency is a reasonable expectation; direct conversion from energetic charged particles to electricity is a possibility, and conversion of synchroton radiation from the plasma to electricity by a rectifying antenna is also possible.

Calculation based on the known concentration of helium-3 in lunar regolith yields the excavation rate. Conceptual designs for mining machines and processing equipment were developed by the University of Wisconsin. The number of miners is based on the UW design. Each miner and the associated processing equipment, according to their conceptual design, adds up to 45 metric tons. This sets the space transportation requirement for delivery to the Moon.

Power requirements are an issue. Most of the power needed is thermal power; significant additional power is needed for refrigeration since the separation of helium-3 from helium-4 occurs at cryogenic temperature. Thermal power can be delivered by solar concentrators or possibly by nuclear reactors. The thermal power delivery temperature is about 600°C; a 200 MW_{th} reactor might be less massive than solar concentrators, and would allow day and night operation of the processing plants.

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Helium-3 System Sizing

Helium-3 Quantity for 10 GWe

$$10\ \text{GW-yr} \times \frac{8760\ \text{E6 kWh}}{\text{GW-yr}} \times \frac{3.6\text{E6 j}}{\text{kWh}} \times \frac{1\ \text{kg conv to energy}}{8.9875\ \text{E16 j (e = mc2)}} \times \frac{931\ \text{MeV/amu (100\% conv.)}}{18.3\ \text{MeV/3 amu (fusion)}} = 535\ \text{kg He3 at 100\% plant eff'y}$$

[About 1 ton at 50 % efficiency.]

Mining System

Usable Helium-3 concentration 8.4 parts per billion (of regolith excavated)

Regolith excavated = 1 ton/7E-9 = 145 million tons; processed after beneficiation = 120 m. tons.

One miner estimated to excavate 10 million tons/yr; need 20 miners.

Byproducts: H_2 6100kg/kg ^{3}He; H_2C 3300 kg/kg;

Surface Power

$$120\ \text{E9 kg} \times 600\text{C} \times 0.1\ \text{sp. ht.} \times \frac{0.2\ \text{recup factor} \times 4186\ \text{j/Kcal}}{3.6\ \text{E6 j/kWh} \times 8.76\ \text{E6 kWh/MW-yr}} = 190\ \text{MW}$$

250 + megawatts with reasonable efficiency factors.

What we know:

- ^{3}He reduces fusion reactor radiation contamination & other radiation problems by a factor of 50.
- There are almost unlimited quantities of ^{3}He on the Moon (at low conentrations).
- Use of byproducts in the transportation system can reduce costs to the target range.
- ^{3}He is worth 1 to 2 million dollars per kilogram as a fusion fuel.

Comparison of Transportation Options

Transportation cost to the Moon for mining and processing equipment may be significantly ameliorated by using the hydrogen and oxygen byproduct of helium-3 extraction for operation of the space transfer vehicle (STV) fleet. The facing page shows the results of a simple network analysis for several options of lunar propellant use. If all space transfer propellant must be launched from Earth, the total Earth launch requirement is about eight times the net payload delivered to the Moon. This assumes use of aerobraking for return to low Earth orbit; without aerobraking the ratio of masses is much worse. For this baseline estimate, we assumed aerobrake mass of 15% of the payload (recovered hardware plus any mission payload) of the aerobrake.

If lunar oxygen is supplied to the lunar descent/ascent vehicle (STV operations are assumed to use the lunar orbit rendezvous - LOR - mode), the Earth launch requirement is reduced by about 32% at the cost of 1427 tons per year lunar oxygen production. If lunar oxygen is also carried to lunar orbit by the lander/ascent vehicle and there supplied to the Earth/Moon transfer stage, so that it gets all its oxygen from the Moon, the Earth launch requirement actually goes up, and a very large lunar oxygen production is required. If the aerobrake mass can be reduced to 10%, a slight payoff is realized in that the Earth launch requirement beocmes slightly less than that for the case of supplying lunar oxygen only to the lander/ascent stage.

If lunar hydrogen is alsc available, as is expected for the helium-3 mining case, the Earth launch requirement is dramatically reduced and the lunar oxygen production requirement is much less than needed for the oxygen-only case. Tradeoff analyses indicated that use of lunar-produced hydrogen and oxygen yields the least overall transportation cost, provided that the lunar propellants are byproducts of helium-3 production.

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Comparison of Transportation Options

ADVANCED CIVIL SPACE SYSTEMS

Launch & Propellant Requirements in Tons

To Place 1000T/yr on Lunar Surface

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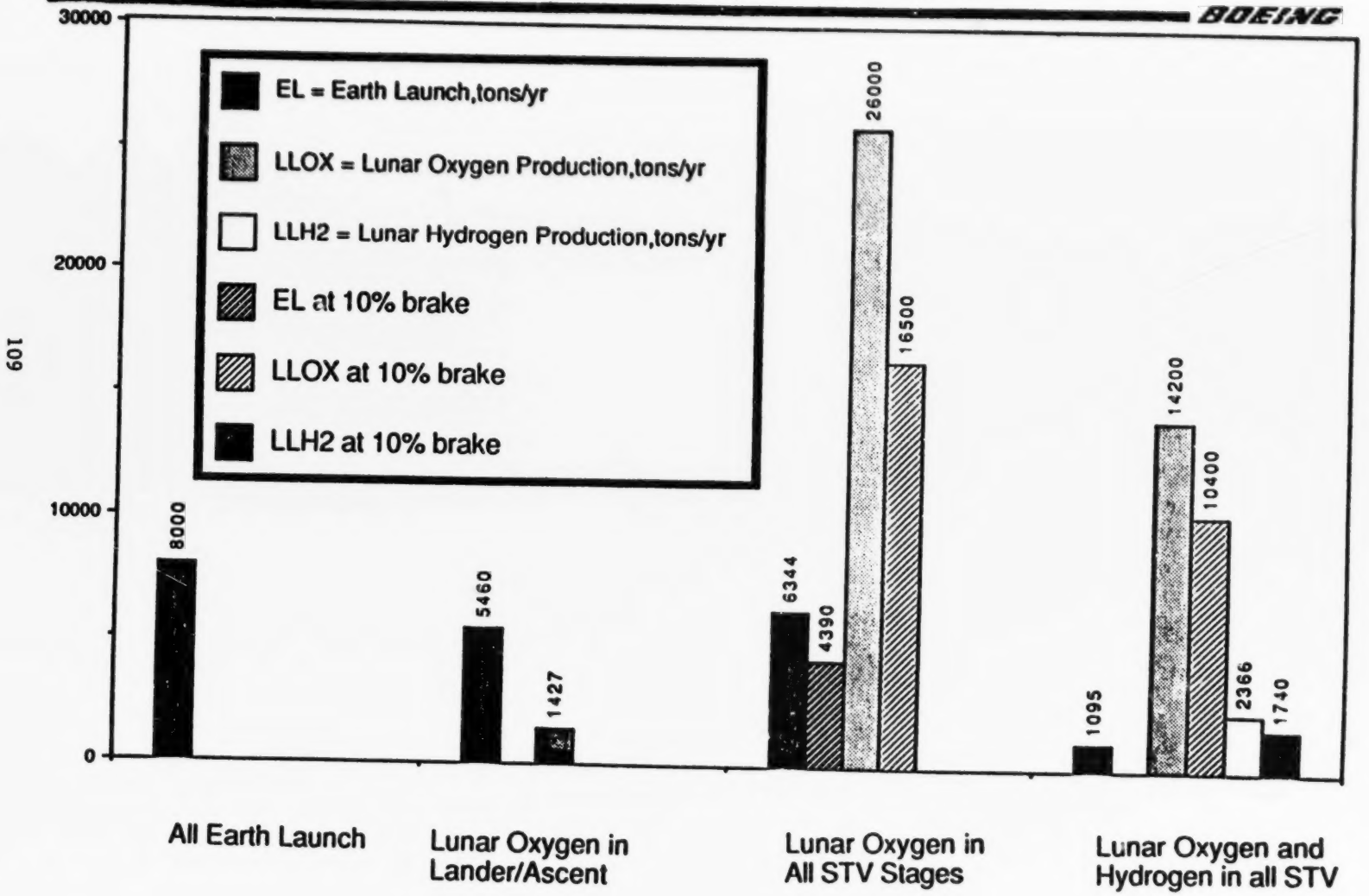

Total Lunar Transportation Cost

The transportation network analysis alluded to above included calculation of vehicle and fleet sizes. These results were used to estimate an overall lunar transportation cost. The cost analysis summarized on the facing page used a commercial approach, including a reasonable return on investment in the luanr STV fleet and a short (5 year) writeoff period. Earth launch costs were based on an expected capability of a Shuttle-C adapted to this mission, including a recoverable propulsion/avionics module. Projected Earth launch costs for an Advanced Launch System (ALS) are about half the figure quoted here.

The target launch cost to make lunar helium-3 commercially economic, assuming the University of Wisconsin mass figures for mining and processing equipment, is about $3000/kg. As indicated, a relatively unsophisticated system is projected to achieve acceptable cost. A reasonable attempt to optimize the system, e.g. by incorporating an ALS, would bring the projected costs down to the $2000 - $2500 range.

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Total Lunar Transportation Cost

Transport Case 4 - Lunar hydrogen and oxygen byproduct used for all STV operations.

Earth launch 1095 tonnes per year.

Lunar STV fleet average unit cost $670 million; six vehicles.

Annual cost = unit investment @ 15% ROI/5 years + 10% annual spares & ops = 40%/yr.

Lunar fleet cost = 40% x $670 million X 6 vehicles = $1608/kg.

Launch cost = 1095 tonnes x $1425/kg = $1560/kg.

Total $3168/kg.

<u>Note:</u> This is not an optimized system. It indicates that costs in the target range are achievable with modest improvements on present-day space transportation systems.

We would expect an optimized system to deliver somewhat, but not dramatically, lower costs.

Helium-3: What We Know

Quite a lot is known about the helium-3 concept. The resource estimates are based on measured quantities of helium-3 in lunar samples returned to Earth during the Apollo program. Although the concentration is very low, the total resource is enormous.

The importance of Helium-3, as described in Appendix B2, is based on estimates of the simplification to fusion reactors (e.g. elimination of the lithium blanket) that it offers, and the increased lifetime that results from the fifty-fold reduction in neutron flux. The result is an estimated economic value of helium-3 on Earth of $1000/gram. The estimate is quite conservative in that these simplifications and increases in life and availability may mean the difference between economic and uneconomic fusion reactors.

Processes for extraction and separation of helium-3 are well-known. We may, of course, find better processes.

The real space transportation issue is delivery of the mining and processing equipment to the Moon. Return of the helium-3 is a relatively trivial issue. Straightforward evolution of present-day space transportation technology can bring costs into the acceptable range; new inventions are not required. A key to the acceptable costs is the use of the hydrogen and oxygen byproducts of helium-3 production as rocket propellant.

Helium-3: What We Know

- Recoverable Helium-3 resource on the Moon is huge.
- Helium-3 as fusion fuel has potential value on the order of $1000/gram.
- Helium-3 can be extracted from regolith by bulk heating.
- Processes for separation of helium-3 from the (much greater) volume of other volatiles are well known.
- The space transportation cost issue is delivery of mining and processing equipment to the Moon (not return of helium-3).
- Hydrogen and oxygen propellants for operation of the space transfer vehicle fleet can be produced as a byproduct of helium-3 production.
- Space transportation cost estimates indicate economically acceptable costs, based on University of Wisconsin estimates for mass of mining and processing equipment.

Lunar Helium-3 Issues

Since the principal economic issue associated with lunar helium-3 is the space transport cost for delivery of mining and extraction equipment to the Moon, the mass of this equipment is a critical issue. The definitions that presently exist are very preliminary conceptual designs. A much more detailed definition is needed, including many trade studies. Some or even much of the mass of equipment might be lunar-produced from indigenous resources, reducing the transportation burden.

Fusion reactor costs, and the benefits in reactor investment and operation costs (and also potential benefits in plant availability) need better definition, so that we can attach a more confident value to the cost benefits of helium-3. Optimistic estimates of the value of helium-3 might place its value as high as $2000/gram.

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Lunar Helium-3 Issues

Definition of mining and extraction system.

- Mass delivered to Moon is a critical financial factor.
- Optimum extraction means (present baseline is thermal bulk heating of regolith; options include grinding and reagent methods).
- Power delivery - thermal power should come from direct concentration of solar energy; electrical systems would be too massive.
- Centralized vs. distributed processing trade.
- Cost of lunar installations.

Cost benefits of helium-3 versus tritium (value of helium-3)

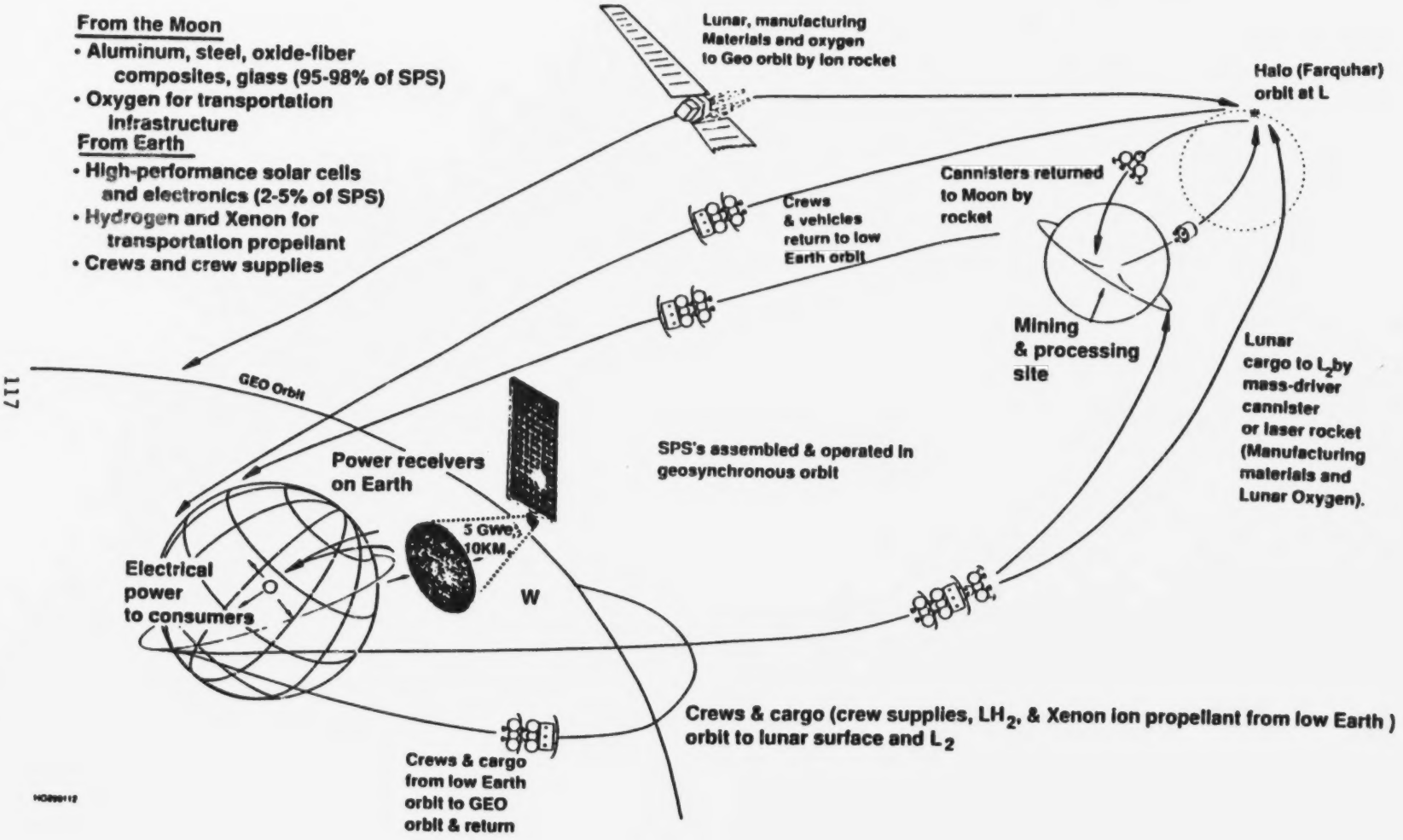
Fusion rector costs

Operations Concept for Manufacture of SPSs from Lunar Resources

Solar power satellites were studied in considerable depth about ten years ago. Those studies considered mainly a scenario in which all of the satellite hardware would be delivered to geosynchronous orbit from Earth. Significant issues were raised as to the very low space transportation costs projected by the studies. If the transport costs were as high as suggested by the critics, the SPS system would be economically infeasible.

Certain contemporary studies recommended that most of the mass, 95% or more, of an SPS could be produced from lunar materials. Space transportation costs from the Moon to geosynchronous orbit were argued to be far less than from the Earth's surface. A representative transportation scheme is illustrated on the facing page. The lunar libration point L2 would ba a major staging base or node. Lunar-produced cargo would be launched to L2 by electromagnetic catapult (mass driver). Transportation from L2 to geosynchronous orbit and return would employ solar electric propulsion. In the scenario illustrated, hydrogen propellant for cryogenic rockets and inert gas propellant for electric propulsion systems is supplied from Earth. We conducted trades to optimize the transportation system, leading to the concept shown.

Operations Concept for Manufacture of SPSs From Lunar Resources


From the Moon
• Aluminum, steel, oxide-fiber composites, glass (95-98% of SPS)
• Oxygen for transportation infrastructure
From Earth
• High-performance solar cells and electronics (2-5% of SPS)
• Hydrogen and Xenon for transportation propellant
• Crews and crew supplies
Lunar, manufacturing Materials and oxygen to Geo orbit by ion rocket
Halo (Farquhar) orbit at L
Crews & vehicles return to low Earth orbit
Cannisters returned to Moon by rocket
Mining & processing site
Lunar cargo to L2 by mass-driver cannister or laser rocket (Manufacturing materials and Lunar Oxygen).
GEO Orbit
Power receivers on Earth
SPS's assembled & operated in geosynchronous orbit
5 GWe
10KM
W
Electrical power to consumers
Crews & cargo (crew supplies, LH2, & Xenon ion propellant from low Earth) orbit to lunar surface and L2
Crews & cargo from low Earth orbit to GEO orbit & return

Solar Power Satellite System Sizing

Solar power satellites optimize to very large unit size, because of the physics of power beaming. The wavelength selected by the SPS systems studies was 12 cm. (2.45 GHz) in the industrial microwave band. An alternate industrial band is available at about 5.6 GHz. It is projected to have somewhat less efficiency, and greater losses associated with severe weather. A 5-GHz system would, however, optimize at 1 - 2 GWe.

Thermal limits of one kind or another result in power density limits at both the transmitter and receiver. Plugging these limits into system optimizations is the mechanism that determines optimum unit size.

The facing page provides rough estimating rules for the mass of solar collectors and power transmitters.

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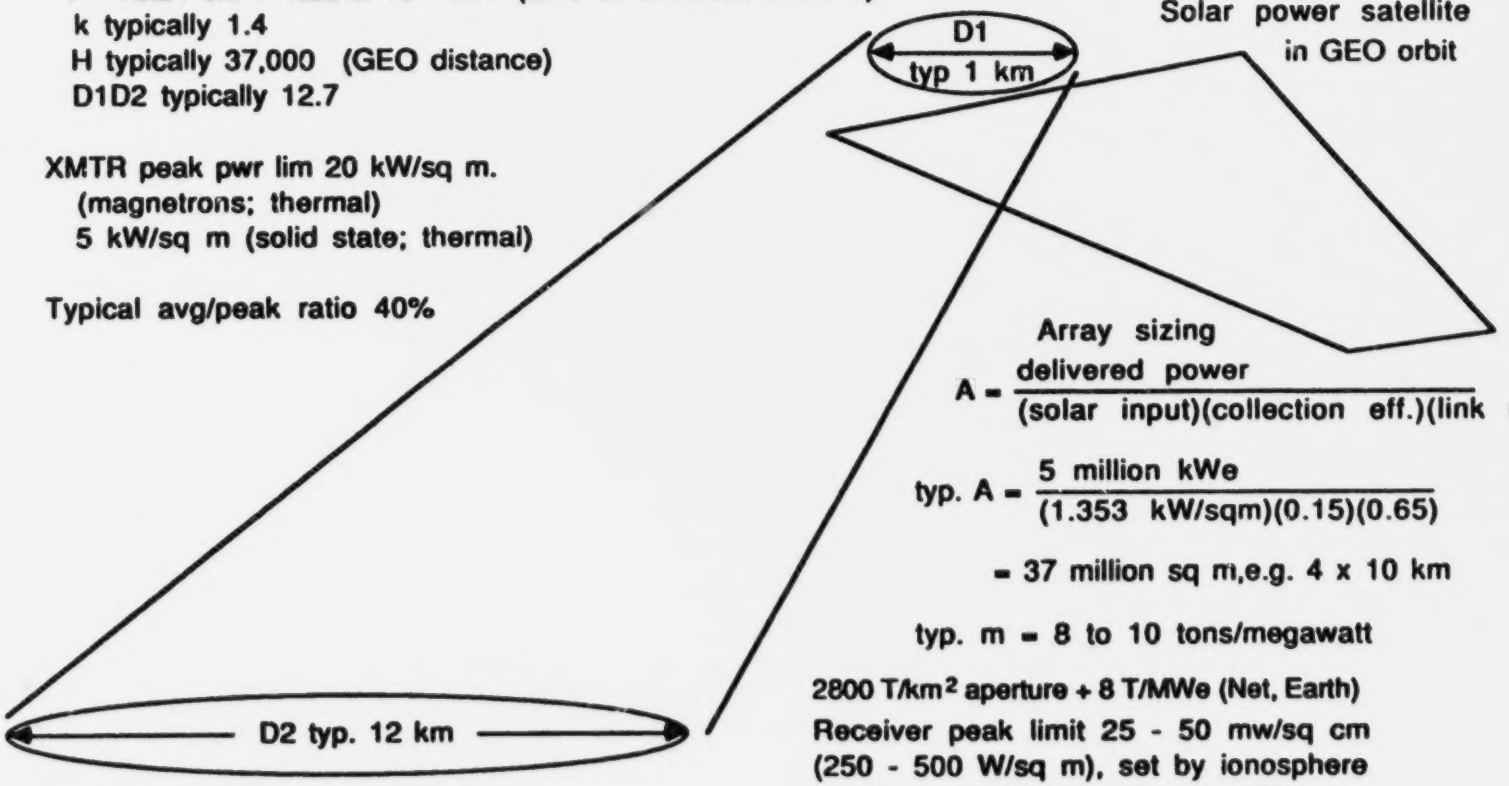
Solar Power Satellite System Sizing

Aperture product: D1D2 = 2klH (coherent microwave physics)
l = 12.24 cm = 1.224×10^{-4} km (2.45 GHz industrial band)
k typically 1.4
H typically 37,000 (GEO distance)
D1D2 typically 12.7

XMTR peak pwr lim 20 kW/sq m.
(magnetrons; thermal)
5 kW/sq m (solid state; thermal)

Typical avg/peak ratio 40%



Power receiving station on Earth

$$A = \frac{\text{Array sizing}}{\text{delivered power}}$$
$$\text{(solar input)(collection eff.)(link ef}$$

$$\text{typ. } A = \frac{5 \text{ million kWe}}{(1.353 \text{ kW/sqm})(0.15)(0.65)}$$

= 37 million sq m,e.g. 4 x 10 km

typ. m = 8 to 10 tons/megawatt

2800 T/km^2 aperture + 8 T/MWe (Net, Earth)

Receiver peak limit 25 - 50 mw/sq cm (250 - 500 W/sq m), set by ionosphere heating. Typ. avg/peak ratio 20%

Solar Power Satellite - What We Know

Microwave power beaming has been thoroughly demonstrated in laboratory and field tests. Laboratory tests many years ago demonstrated end-to-end electrical power to electrical power efficiencies greater than 50%. Field tests at JPL in 1975 demonstrated receiver efficiencies of about 85%. DC to RF conversion approaching 90% has been demonstrated using magnetrons in laboratory setups; klystrons have reached 70%. Correlations between theory and experiment for power beaming are well understood.

Conversion of sunlight to electricity by photovoltaics is well-understood. While selection of the preferred photovoltaic system would require a substantial amount of work, several options exist today with performance superior to that assumed by the SPS systems studies of 1976-1981. These systems studies, adjusted to allow for recent technology advances, provide a sound mass and performance data base.

Use of lunar materials offers a significant reduction in transportation costs for the emplacement of SPSs in geosynchronous orbit. Most of the raw materials needed to fabricate SPSs are available on the Moon. A few years ago, it was feared that increased in-space fabrication costs would offset the transportation savings, but advances in automation and robotics, applicable to space assembly, alleviate that concern.

Large-scale use of lunar materials will reduce needed Earth launch rates by at least a factor of ten compared with construction of SPSs entirely from Earth-derived materials. This substantially eliminates the environmental concerns associated with extremely high launch rates.

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Solar Power Satellite - What We Know

Efficient power transfer proven in laboratory and field experiments.

Magnetrons identified as most effective microwave power transmitters.

Performance of space photovoltaics well understood and proven.

Extensive design studies by joint DOE-NASA program provide sound mass and performance data base.

Raw materials for fabrication of 95% - 98% of an SPS are available on the Moon.

Space transportation cost analysis show potential for significant cost savings through use of lunar materials.

Use of lunar materials would reduce Earth launch requirements by factor of 10 compared to earlier studies, substantially eliminating environmental concerns of high launch rates.

SPS Issues

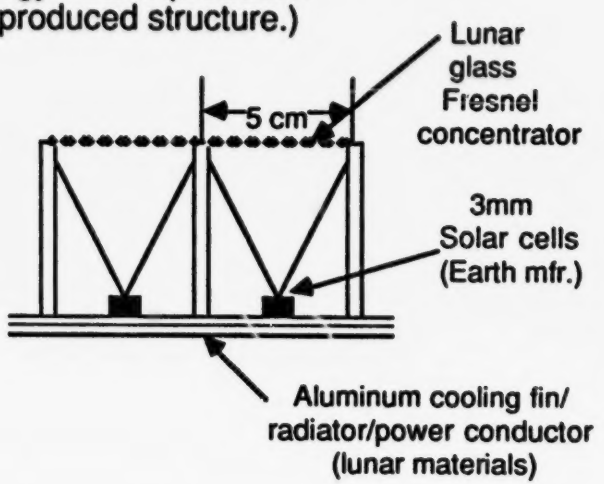
The most important SPS issues deriving from the lunar production scenario are described on the facing page.

The most promising design strategy appears to be use of high-performance photovoltaics with high concentration of sunlight. This strategy could permit operation of the photovoltaic system at efficiency approaching 30%. Almost all of the mass of material is in the concentration, structural support, and power conductor systems. Even if the photovoltaics are produced on Earth, the lunar material contribution to the SPS can exceed 95% mass.

Lunar and space manufacturing and assembly systems need definition. Contemporary thinking about space assembly systems would lead to (1) use of the SPS as its own assembly platform, eliminating the need for a large and expensive assembly facility, and (2) heavy reliance on automation and robotics assembly operations, reducing the human crew at the geosynchronous assembly station from hundreds to a few. If these potential advances can be realized, the cost for assembly operations can be controlled to a modest figure that is a small part of the overall SPS cost.

SPS Issues

- Best High-efficiency, high concentration collector design compatible with lunar materials and space manufacture (Design strategy : Earth-produced high-performance, high-concentration solar cells in lunar-produced structure.)
  - Definition and cost of lunar mining and manufacturing systems
- Definition and cost of space manufacturing and assembly systems
- Definition and cost of economically optimal space transportation and operations systems (Strawman system ROM cost about $12 billion/10GWe SPS capacity emplaced at GEO)


5 cm
Lunar glass Fresnel concentrator
3mm Solar cells (Earth mfr.)
Aluminum cooling fin/ radiator/power conductor (lunar materials)

Evolution of Lunar Power System (LPS)

The lunar power system concept is an approach to minimizing space transportation requirements for space-collected power beamed to Earth. The space power collectors and beaming systems are constructed on the Moon itself, mainly of lunar materials. Large phased-array antennas constructed on the Moon produce near-field microwave beams focused on power receivers (rectennas) on Earth. Because of the great range (385,000 km) it is necessary to use a large transmitter aperture and near-field focusing to obtain reasonable receiver apertures on Earth.

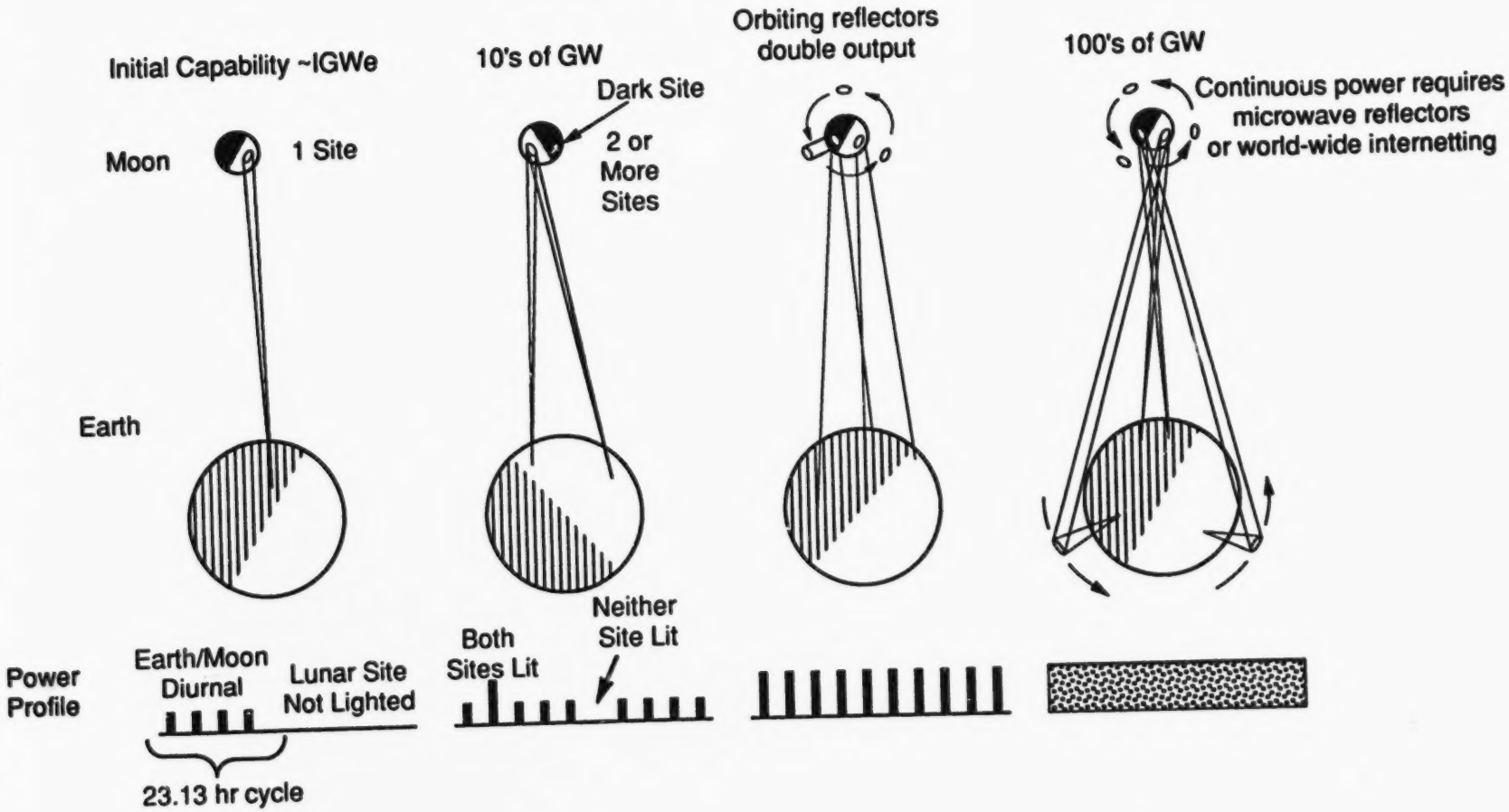
Since the Moon always keeps one face towards Earth, a transmitter on the near side can always transmit to Earth. However, the Earth rotates relative to the Moon, so that unlike the geosynchronous SPS, a lunar power transmitter cannot always transmit to the same site on Earth. The LPS, then, is inherently a global system. Also, since the Moon rotates relative to the Sun, any single site on the Moon will be sunlit for about 14 (Earth) days and dark for about 14. Power availability can be increased, but not made continuous, by locating a second power station near the opposite limb of the Moon.

Basic to the LPS concept is multi-beaming, so that one 50,000 megawatt power transmitter site on the Moon would feed numerous power receivers on Earth. This avoids any one receiver site being of excessive unit size. A phased-array antenna can generate multiple beams by synthesizing what amounts to an interference pattern.

A system of orbiting optical reflectors that would illuminate otherwise dark power sites on the lunar surface could enable continuous transmission to Earth. Lunar beamed power would still be available to any particular Earth site only when that site faced the Moon. A second system of orbiting microwave reflectors could provide continuous power to Earth receiving sites.

The lunar power system is seen to be inherently a global system, and one that is truly efficient only on a very large scale.

Evolution of Lunar Power System to Continuous Baseload Power Requires Auxiliary Reflectors at Earth and Moon

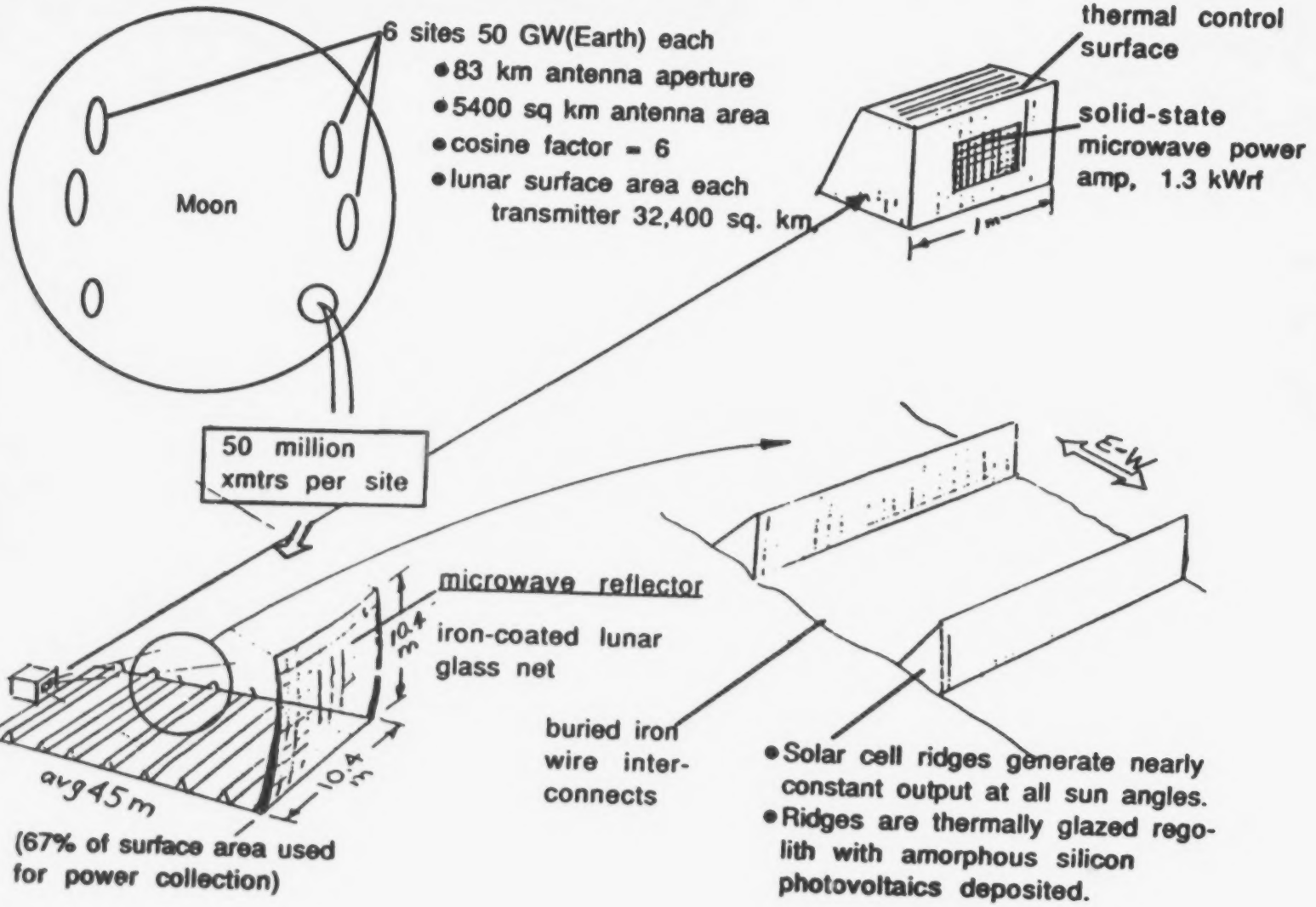


Lunar Power System Concept

A look at the actual power installations on the Moon reveals millions of modular microwave power transmitters at each of several sites. Each modular transmitter consists of a solar cell collection field, geometrically arranged to have nearly constant power output as the Sun slowly crosses the lunar sky; a microwave power generator and phase control system, and a reflector antenna. All of the power collection, conversion, and transmission equipment is presumed to be lunar-manufactured except for microwave generators and phase control electronics.

The field of transmitter antenna reflectors would appear as a filled aperture as viewed from Earth.

Lunar Power System Concept


6 sites 50 GW(Earth) each
• 83 km antenna aperture
• 5400 sq km antenna area
• cosine factor = 6
• lunar surface area each transmitter 32,400 sq. km
Moon
thermal control surface
solid-state microwave power amp, 1.3 kWrf
1 m
50 million xmtrs per site
E-W
microwave reflector
iron-coated lunar glass net
10.4 m
10.4 m
avg 45 m
(67% of surface area used for power collection)
buried iron wire inter-connects
• Solar cell ridges generate nearly constant output at all sun angles.
• Ridges are thermally glazed regolith with amorphous silicon photovoltaics deposited.

Lunar Power System - What We Know

Iron and glass are readily producible on the Moon. While amorphous silicon solar cells will be more difficult to produce, silicon is very plentiful on the Moon. Microwave power generators will probably use gallium arsenide and be produced on Earth, as will the power and phase control electronics.

Distributed array power beaming appears feasible. There are concerns as to the efficiency of distributed antennas which are not on a contiguous plane, and very high phase control precision is needed to produce the near-field beam focused on Earth at a range of 385,000 km (about 3 billion wavelengths).

Relatively modest minimum power levels are feasible (if any power level is feasible). Since a low power density antenna does not require a structure to support it (it is on the surface of the Moon), the cost penalties attendant to low power density space antennas do not apply.

Finally, the LPS is inherently a global, large-scale system. It cannot deliver baseload power except with optical reflectors orbiting the Moon to provide continuous solar illumination, and cannot deliver baseload power to any particular region unless systems are globally interconnected.

Lunar Power System - What We Know

Construction materials needed are available on the Moon.

Theory supports concept of distributed phased array power beaming antenna (performance analysis needed).

Smallest feasible power size is on the order of 1 GWe. Low power density antenna does not incur cost penalties that would occur if one had to build a structure to support it.

System augmentation, by reflectors orbiting both the Moon and Earth, needed to deliver baseload power.

LPS Installation Operations Sizing

The scale of operations for the LPS is truly enormous, and not well understood. What is involved in making ten transmitter unit installations per minute is a big question. Preparation of 25 square meters per second of lunar surface area is a huge operations rate. If the 20-mile freeway spur between I-65 and Huntsville, Alabama could be built at that rate, it could be finished in two days instead of the anticipated three years. While freeway construction seems much more complex than the lunar operations for LPS, such comparisons certainly give one pause.

LPS Installation Operations Sizing

10 GWe/yr = 5 million transmitter units/yr, 10 per minute.

Regolith moved/shaped: 2340 sq km per year, to 30 cm average depth, = 1.4E9 tons/yr,
= 140 machines at 1E7 tons/yr each.

Prepared area (glazed, solar cells) = 793 sq km/yr = 25 sq m/sec.

Thermal power for glazing = 25 sq m x 0.001 m x 2000 kg/sq m x 0.1 sp ht x 4186 j/Kcal
= 21 E6 j/sec, 21 megawatts, 150 kW/machine

With 140 machines, each one does 100 sites/day.

Lunar Power System Issues

The lunar power system transmitter requires very high phase control performance even compared to the SPS. While the SPS is a planar-wave far-field transmitter, the LPS must generate a set of concave (focused) near-field waves of much greater precision. Detailed performance analyses for the transmitter systems are needed to establish the transmitter unit design and determine reflector requirements. The transmitter phased array can partially correct for inaccuracies in the reflector, but only to the extent that such inaccuracies do not cause multiple ray paths.

The lunar surfacing job to be done and the solar cell deposition machine need better definition to scope the difficulty of the operations tasks. Finally, an analysis of the integration of LPS power into Earth power grids and the distribution of LPS power on Earth needs to be done to establish the generating capacity displacement capability of LPS. (This means, "how much generating capacity (if any) of another type can one kilowatt of LPS power replace?" The answer is very important to determining the value in dollars per kilowatt for LPS generating capacity.)

Lunar Power System Issues

Technology and design requirements on lunar power transmitter antenna for high-efficiency multi-beam power transfer:

- Transmitter unit design
- Reflector - shaping and accuracy requirements

Extent of lunar "surfacing" job; depth of regolith to be moved/smoothed.

Definition of solar cell deposition machine.

Scope and scale of lunar surface operations.

Integration into power grids; power distribution on Earth.

Basic Statistics of the Energy Options

The lunar operations scales of the three concepts are very different. The SPS involves much smaller lunar operations than the other options, but requires much greater space transportation infrastructure, and for efficient large-scale delivery of lunar materials to space (the other options do not require this), needs development of a mass driver and a multi-megawatt solar (or nuclear) electric propulsion system. This chart emphasizes differences in lunar operations; space transportation needs are compared later.

The nature of the operations for these systems is somewhat different. A given scale of operations for the helium-3 system delivers a certain quantity of mining operations equipment to the Moon each year; this equipment increases the production rate for helium-3 fuel, and correspondingly increases the supportable generating capacity on Earth. The SPS is very similar; a given scale of operations leads to a given construction rate, and hence a given rate of increase in generating capacity on Earth. In both cases, one should presume a certain requirement for operations and maintenance of capacity, and this would increase as the generating capacity is increased. With a fixed space operations capability level, the O&M requirement would increase with capacity and would eventually saturate the fixed space operations capability, displacing the ability to further increase generating capacity.

In the LPS scenario, a given scale of space transportation operations delivers equipment to the Moon capable of a given costruction rate. Thus continued operation of the space transportation system leads to an ever-increasing construction rate, rather than maintaining a constant construction rate as is the case with the other scenarios. This is a powerful advantage if it is valid.

There are two caveats in this: (1) the LPS construction rate may be controlled mainly by lunar surface operations that require support from Earth; and (2) the LPS construction rate may be controlled by construction of orbiting reflectors or other support systems that require continuing space transportation operations. Neither of these caveats is understood; analysis and simulations are needed.

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Basic Statistics of the Energy Options

Producing 10 GWe per Year

	Lunar Helium 3: (10 GWe Generating Cap)	SPS at GEO (10 GWe Inst'l'd per year)	Lunar Power System (10 GWe Inst'l'd per year)
Tons/Yr of Regolith	200 million (to get 1.3 tons Helium-3)	2 million	1400 million
Processing Depth	1 meter	1 meter	30 cm*
Area/Yr	200 square km	1 square km	2340 square km (actually used, 60% of site)
# of Mining Machines	20	2 (plus spares)	140
Processing Plants	Volatiles separation and liquefaction	Aluminum 40,000 T Glass 40,000 T Oxygen 25,000 T Misc. 10,000 T	Silicon Iron Glass (surface glazing is part of "miner".)
Lunar Surface Power	250 + MW	500 MW	400 MW
Mass Drivers	(none)	3 at 100 kg/min.	(none)

*Criswell assumes 2.7 cm avg depth

"Mining" Comparison

Helium - 3	SPS	LPS
Excavate regolith, 200 million tons/yr, 200 sq km at 1 meter depth	Excavate regolith, 2 million tons/yr, 1 square km per year at 2 meters	Excavate/move/shape regolith, 1400 million tons/yr at 30 cm depth*, 2340 sq km
Heat to drive off volatiles	Beneficiate for aluminum, glass, oxygen, & other production.	Beneficiate for glass & silicon production
Pressurize & collect volatiles	40,000 T Aluminum 40,000 T Glass 25,000 T Oxygen 10,000 T Other	Extract native iron
Note		Glaze surface
Process energy, if supplied by fuel cells, would consume about 65,000 kg/d O2 & H2.	Operate mass driver to launch lunar-produced products to L2.	Deposit silicon solar cells & interconnect
		Lay wire

Note: Dr. Criswell's papers assume 2.7 cm depth; the greater depth estimate comes from Boeing studies of lunar surface operations.

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Antenna Sizing and Power Levels for LPS

The facing page shows receiver antenna sizing and power levels reached as an LPS transmitter grows in size at constant transmitter power density. When the transmitter reaches 10 km diameter, its output is about 1 GW_e Earth equivalent, and it is capable of focusing a beam to about 10 km diameter with an average power density of 1.3 milliwatts/cm^2, with peak receiver density of 6 mW/cm^2. Similar results are shown for other transmitter sizes and powers. When the transmitter reaches about 25 km_2 diameter, it generates 5 GW_e with a potential peak power density of 150 mW/cm^2. Since the acceptable peak value is thought to be about 30 mW/cm^2, at this point the transmitter needs to generate at least 5 beams to reduce the power density at each receiver site. As the transmitter continues to grow in size, the power per receiver site and the antenna size at the receiver sites decreases and the number of sites increases.

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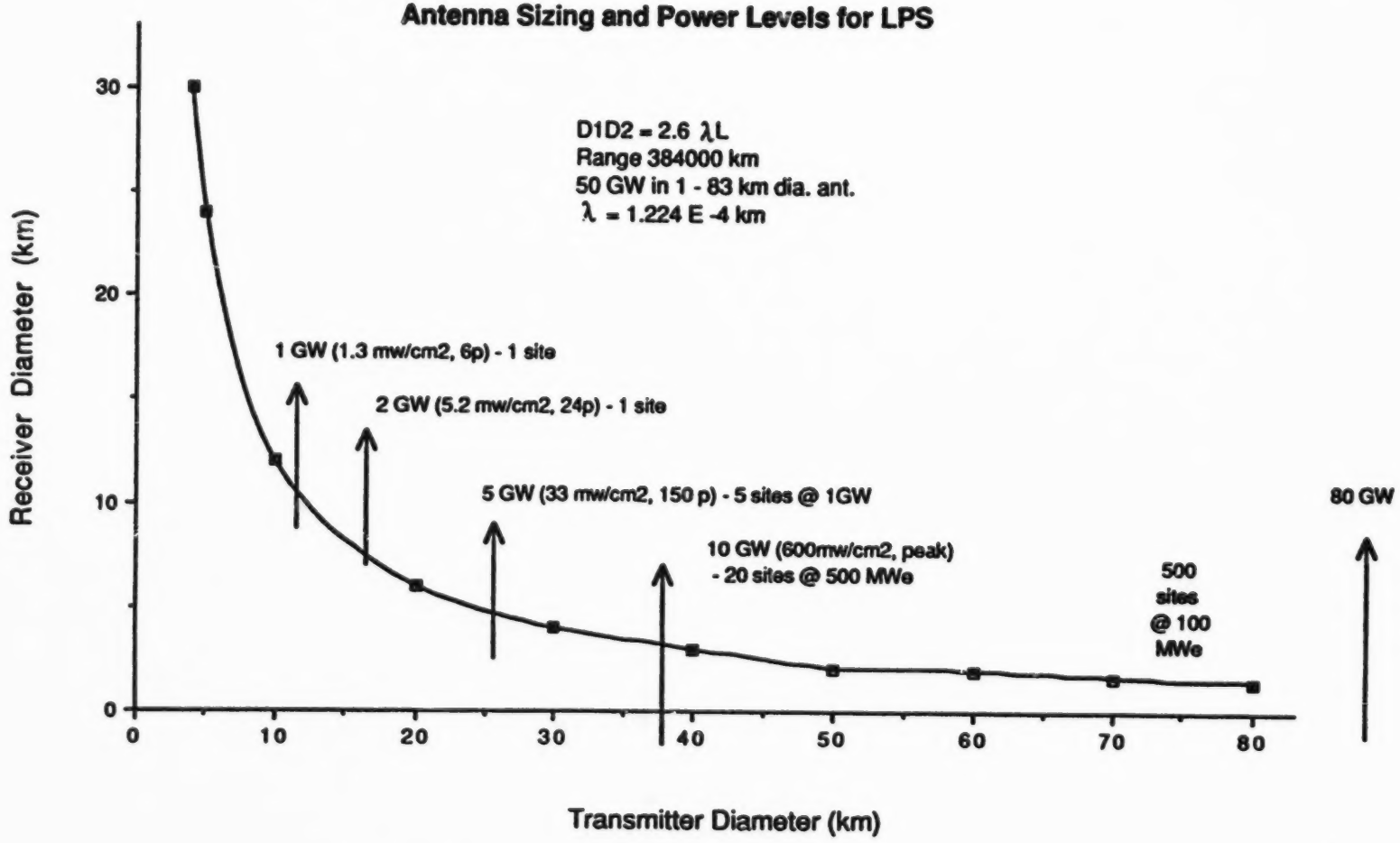
Antenna Sizing and Power Levels for LPS



Concerns/Top Issues

The top issues for each concept are stated here. In the helium-3 case the top issue for space operations is clearly the definition of the mining and extraction system and its mass and cost. One might argue that the feasibility of helium-3 fusion reactors is the top issue, but this is not a space operations issue.

For SPS, a further definition of the processing, logistics, and manufacturing systems for lunar-derived SPS production is the issue. Logistics is better understood than the other factors. We need to know precisely what is being produced on the Moon, how it is packaged and shipped to geosynchronous orbit, and how the assembly process is to operate. Earlier SPS scenarios assumed only final assembly at the GEO site, while the lunar scenario will require much parts fabrication and assembly, in view of the small mass capability per launch of the mass driver. Contemporary/future automation and robotics capabilities need to be included.

The issues concerning the LPS were mainly discussed in the text for the prior chart. The entire lunar surface operations system needs a careful preliminary definition and assessment.

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Concerns/ Top Issues

Helium 3:
- Mining System Definition
- Power rqts and Power Delivery System
  (Electric systems ≈ 20T/MWe = 200 T/miner)

} 45 tons may be much too low

SPS :
- Processing/logistics/Mfr. system to deliver lunar-derived SPS components and/or raw materials to GEO

LPS:
- Scale of surface operations
- Mass of material to be produced
  (major issues are antenna reflectors and depth of regolith to be moved/processed)
- Definition of machine that deposits solar cells

Representative Demonstration Steps

Representative demonstration steps for the options are described here, using analogies to the commonly described demonstration steps for the fusion program. Clearly, in the later phases, as is true for the fusion program, demonstration of a capability to supply energy at an acceptable cost is a key part of the demonstration process.

Representative Demonstration Steps

	Helium-3	SPS	LPS
"Scientific Break-even"	Show that there is Helium-3 on the Moon (accomplished)	Demonstrate efficient power beaming (accomplished)	Demonstrate efficient power beaming (accomplished)
"Ignition"	Demonstrate extraction by practical engineering process	Demonstrate phase control over GEO distance	Analytically validate antenna design & demonstrate phase control over lunar distance
"Engineering Test Reactor"	Demonstrate critical features of processing on the Moon	Demonstrate critical features of lunar materials processing - mat'ls production - transport, e.g. mass driver	Demonstrate critical features of lunar operations - mat'ls processing - solar cell deposition - antenna fabrication
"Prototype"	Deliver useful power	Deliver useful power	Deliver useful power

Plausible Prototype Plant Scales

Prototyping scales are presented here. Clearly, the helium-3 system is the easiest to prototype (from the point of view of space operations; makes no judgement as to the difficulty of demonstrating fusion reactors) since initial recovery and return to Earth of modest quantities of helium-3 is compatible with a few heavy-lift launch vehicle (HLV) flights and with an early lunar base.

The other concepts are driven to larger scales by the physics of microwave power beaming. The SPS is easier than the LPS, and could be demonstrated by a pilot-plant SPS derived entirely from Earth. If the demonstration is derived from Earth, certain key technical demonstrations remain, including lunar processing and mass driver operations.

Plausible Prototype Plant Scales

Helium-3	SPS	LPS
Deliver one prototype miner with power supply and pilot volatiles plant	Produce 500 MWe pilot plant [7000 T at GEO]	Produce 1 GWe pilot plant (10 km dia site & 10 km Earth receiver)
1 MWe power on lunar surface + 10 MWth for miner	Operate pilot plants for aluminum, oxygen and glass on lunar surface	5 - 10 mining & construction machines
Return Helium-3 to Earth: 10 kg 3 times/yr	5 MWe power on lunar surface	Circa 2000 T Earth-mfr. hdwe Microwave amps Power processors Electronics Thermal control hdwe Silicon refinery
Roughly 4 HLV flights at 140 T; feasible with early lunar base	1 mass driver on lunar surface	Few MWe power
	Robotics suite to GEO	Roughly 80 HLV flights; advanced lunar base (number could be reduced with in-situ propellant production)
	1 SEPS	
	Roughly 40 HLV flights; advanced lunar base (100 HLVs all Earth produced)	

Strongest Features of Each

Helium-3: Compatibility of demonstration with early lunar base.

SPS: Confidence in the technology (of the basic SPS; not necessarily of producing SPSs from lunar materials).

LPS: Potential leverage for total energy production for a given space infrastructure investment.

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Phase A Definition Needs

The issues raised earlier in this presentation lead to the Phase A definition needs described here. These are important for higher confidence in certain technical feasibility issues, and in economic characteristics of the systems.

Phase A Definition Needs

Helium-3: Mining and processing systems including support systems/equipment. (Adequate definition of crew systems exists.)

SPS: Processing, logistics, and manufacturing systems required to produce SPSs from lunar materials. (Adequate definition of SPS itself exists.)

LPS: Antenna system & its performance; mobile processing machines; overall operations; power grid internetting.

Note: These can be modest efforts if they focus only on key issues.

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IMPORTANCE OF HELIUM-3 FOR THE FUTURE

Gerald L. Kulcinski

I. Historical Perspective

Scientists first proposed the use of thermonuclear energy for civilian applications in the 1950's. This work closely followed on the heels of the Hydrogen Bomb, and it was felt that commercial fusion energy would take only a few decades to perfect. Unfortunately, the difficulty of controlling plasmas (collections of charged particles and electrons) at temperatures 10 times hotter than the center of the sun proved to be much more difficult than originally anticipated. Most of the 1960's was spent developing the field of plasma physics and laying the ground work for a theoretical understanding of plasmas. By the end of the 1960's, and with unprecedented cooperation between U.S. and Soviet scientists, it became apparent that once the plasma physics problems were solved, significant technological progress was also needed to develop a safe and clean power source. Thus, in the 1970's, a dual approach to the problem was pursued: 1) several large plasma physics facilities were constructed to test the theories developed in the 1960's and 2) engineering analyses of power plant designs were initiated to ascertain the technological, economic, safety, and social implications of this new form of energy. Both of these lines of research have been continued in the 1980's with a major milestone of energy breakeven (i.e., the point at which as much energy is emitted from the plasma as it takes to keep it hot) within our grasp as we move into the 1990's. The current plan is to construct several large reactor-like facilities in the 1960's which will produce power in the 500 to 1000-megawatt regime and to use these facilities to test materials and power conversion schemes that might be used in the 21st century.

The worldwide fusion effort is now roughly equal in Europe, Japan, the United States and the USSR. In the early 1980's, approximately 2 B$ per year was being spent on fusion research with the U.S. in the lead of that effort. Today, the total effort is slightly less, but it is clear that the European program has taken the lead from the U.S. and that a strong challenge for 2nd is being made by the Japanese. Altogether over 20 B$ in then current dollars has been spent worldwide on fusion research since the early 1950's.

Further descriptions of the fusion process can be found in the references [1, 2], and only those aspects of this fuel cycle important for this paper will be repeated here. The reader is strongly urged to consult the references for more information on fusion.

II. Relevant Plasma Physics Principles of Thermonuclear Research

Since the early days of the civilian thermonuclear fusion program, scientists had always envisioned that fusing a deuterium (D) and tritium (T) atom at very high temperatures (see equation 1) would prove to be the most favorable for the production of electricity.

$$D + T \rightarrow He^4 + \text{neutron} \qquad (1)$$

Energy released, Q = 17.6 Million Electron Volts (MeV)

There were several reasons why this choice was made, ranging from the fact that the DT cycle ignites at the lowest energy (see Figure 1) to the experience gained from the thermonuclear weapon program in breeding and handling tritium. Two other reactions, listed below, were also briefly considered.

$$D + D \xrightarrow{50\%} \begin{cases} T + H & Q = 4.0 \text{ MeV} \\ n + He3 & Q = 3.3 \text{ MeV} \end{cases} \quad (2)$$

$$D + He3 \rightarrow He4 + H \qquad Q = 18.4 \text{ MeV} \quad (3)$$

Neither of these reactions has received much attention since the 1950's, because they both require higher temperature (see Figure 1) to ignite and because, there was no significant resource of He3 available on Earth.

Several things have changed since those early days of fusion research, and two of these will be addressed in this chapter. First we will address the changing situation in fusion physics, and second we will address the renewed interest in the technological and environmental advantages of the D-He3 cycle. The question of the He3 fuel supply will be addressed at the close of this chapter.

III. State of Plasma Physics as it Pertains to the D-He3 Cycle

Simply stated, the objective in magnetic fusion research is to heat the confined plasma fuel to sufficiently high temperatures (T) at high enough densities (n) and for long enough times (τ) to cause substantial fusion of atoms to take place. Mathematically stated for a reactor using the DT cycle, this can be given as;

$$n\tau \geq 2 \times 10^{14} \text{ seconds per cm}^3 \quad @\ T \geq 20 \text{ keV (200 million °C)} \quad (4)$$

Some perspective on the rate of progress in producing these conditions is given in Figure 2A where the $n\tau T$ values achieved are plotted with respect to when they were first attained and 2B which shows the progress toward energy breakeven. The $n\tau T$ product has been increasing at the phenomenal rate of a factor of 100 every 10 years. In fact in one parameter, namely the temperature T, scientists have actually produced 30 keV ions in TFTR plasmas at the Princeton Plasma Physics Laboratory (PPPL). This is 50% higher than needed for a DT reactor and only a factor of 2 lower than needed for a D-He3 reactor. The appropriate n,τ, and T values required for a D-He3 reactor are

$$n\tau \geq 4 \times 10^{15} \text{ seconds per cm}^3 \quad (5)$$

$$\text{at } T \cong 60 \text{ keV (600 million °C)}$$

A detailed physics analysis shows that the Compact Ignition Torus (CIT) at PPPL could achieve the temperatures above in the mid to late 1990's.

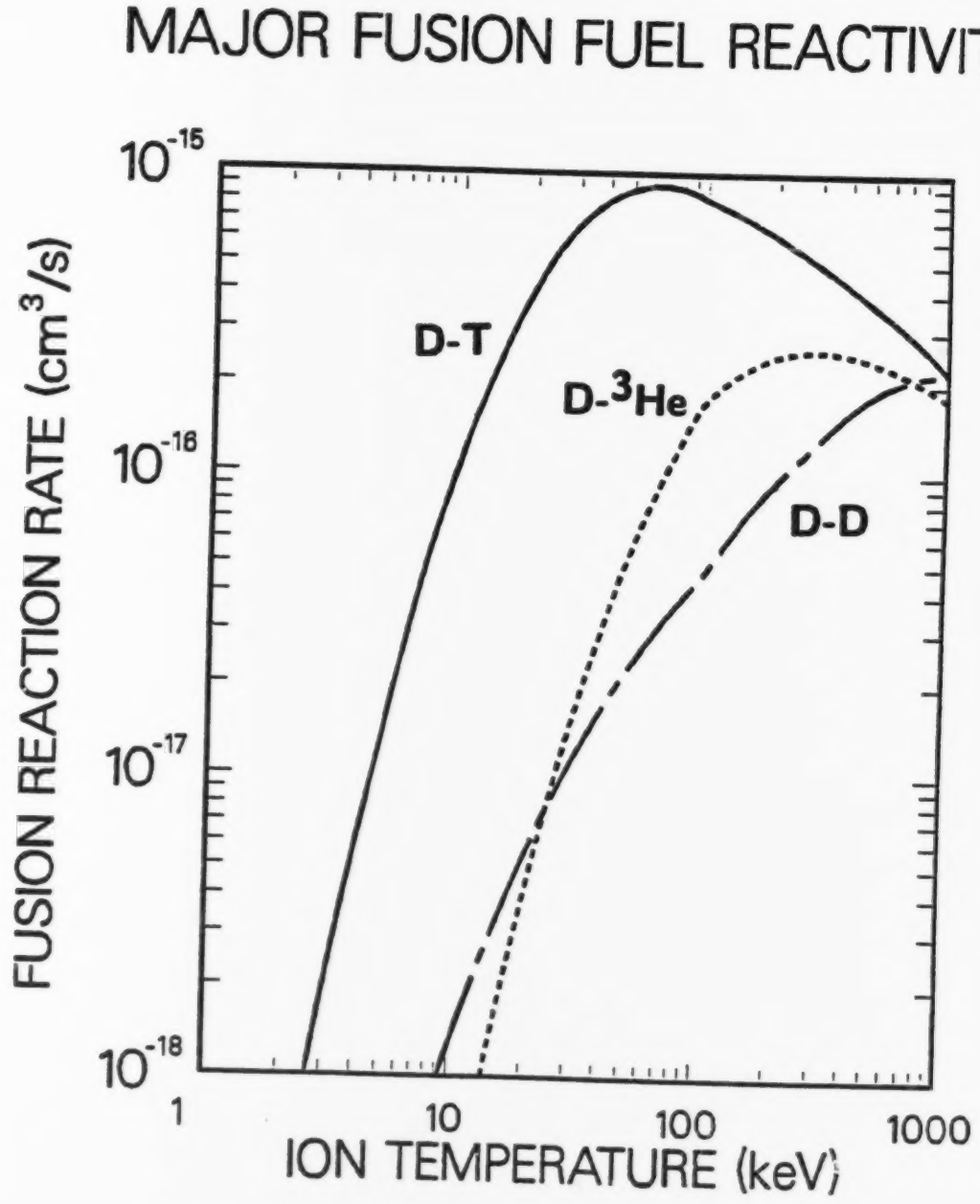

Figure 1. Major Fusion Fuel Reactivities

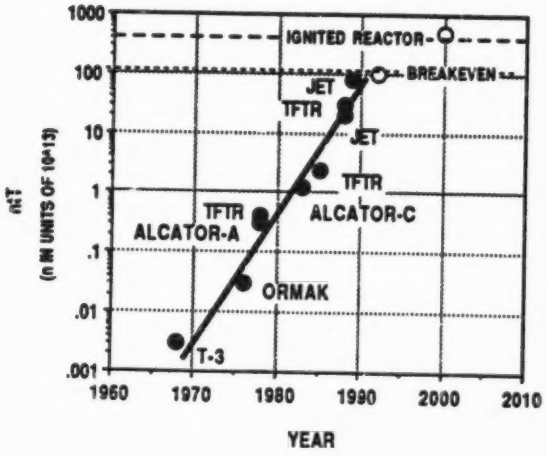

Figure 2A. Steady progress in the 3 major physics parameters for DT fusion.

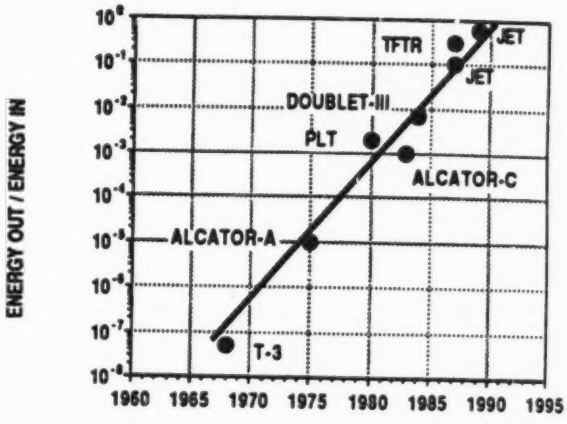

Figure 2B. The progress toward energy breakeven conditions has shown an increase of over 1000 every 10 years for the past 20 years.

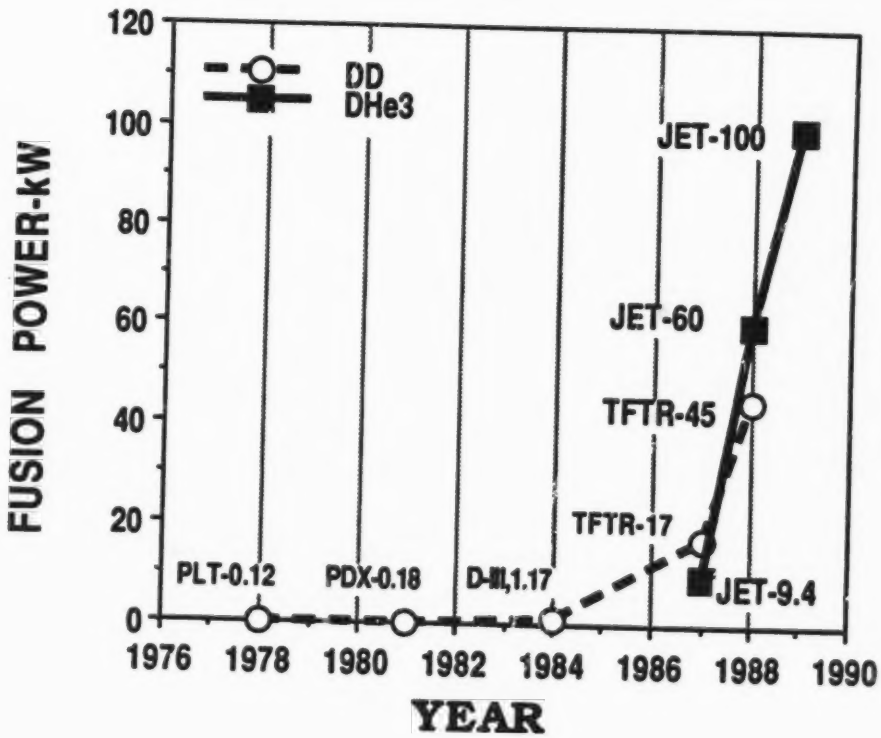

Figure 3. Actual release of thermonuclear energy in the laboratory by the DD and D-He3 reactions from the PLT, PDX and TFTR devices at Princeton, the D-III device at General Atomic, and the JET device in Culham, England.

While it is necessary to reach a $n\tau T$ product of ~ 100 (in units of 10^{13}) for breakeven in DT and a value of 400 for DT reactor operations (Figure 2A), it is necessary to achieve a $n\tau T$ product of 24,000 for the D-He3 reactor. Recent analyses show that such values could be achieved by small modifications of the Next European Torus (NET) or the International Thermonuclear Experimental Reactor (ITER) currently being designed for operations around the year 2000. In other words, despite the factor of 60 required in $n\tau T$ values for a working D-He3 power plant over a DT system, several possibilities to achieve those values are known.

The surprising historical point of the previous discussion is that only a few short years ago, most scientists would have believed it impossible to produce the necessary D-He3 reaction conditions before the year 2020 or even later. However, scientists at JET have recently produced 100 kW of thermonuclear power with the D-He3 cycle (see Figure 3). The possibility that significant power could be produced with He3 before the year 2000 has opened up a whole new class of studies within the past 2 years and caused a complete reassessment of our long-range goals in fusion research.

IV. Technological Benefits of the D-He3 Fuel Cycle

One of the key features of the D-He3 reaction in Equation 2 is that both the fuel and the reaction products (protons and He4) are not radioactive. However, some of the deuterium ions do react with each other producing a small amount of neutrons and tritium. When the cross section and fuel mixtures are included, one can calculate how much of the average energy release is in the form of neutrons (see Figure 4). Whereas the DT cycle releases 80% of its energy in neutrons regardless of the plasma temperature (and the DD cycle releases ~ 50% in neutrons) one can see that operation at ~ 60 keV with a 3:1 ratio of He3/D, can result in release of as little as 1% of the energy in neutrons in a D-He3 plasma.

Why is this important? The radioactivity and radiation damage of reactor components is directly proportional to the number of neutrons produced. Since the energy released per reaction from DT and D-He3 is roughly the same, the problem associated with neutrons can therefore be reduced by almost 2 orders of magnitude (i.e., a factor of 80).

The main technological advantages resulting from these characteristics of the D-He3 fuel cycle, when compared to the DT cycle, are summarized as follows:

a) Increased electrical conversion efficiency.
b) Reduced radiation damage.
c) Reduced radioactive waste.
d) Increased level of safety in the event of an accident.
e) Lower cost of electricity.
f) Shorter time to commercialization.

Only a very brief comment on each of these features will be made here and the reader is referred to several recent publications by the authors for a more in-depth analysis.

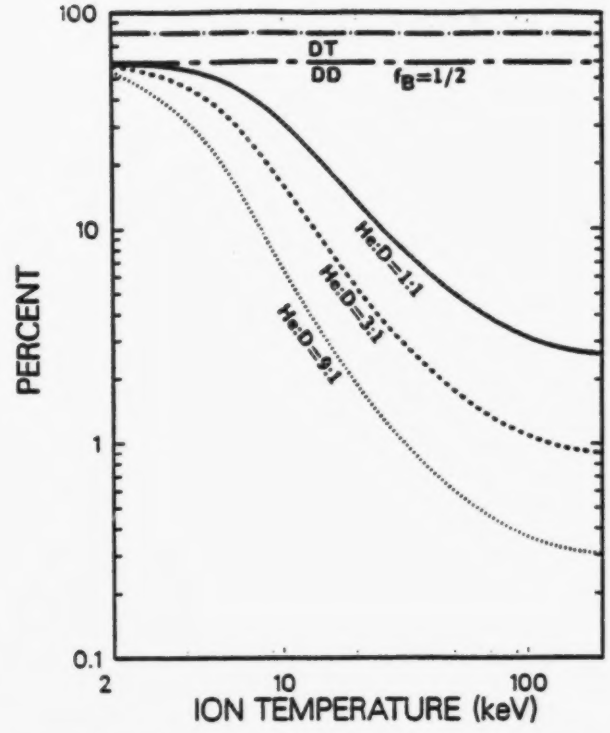

Figure 4. The percent of thermonuclear energy released in the form of neutrons by the DT, DD, and D-He3 fuel cycles. Note the variation of He3 to D ratio.

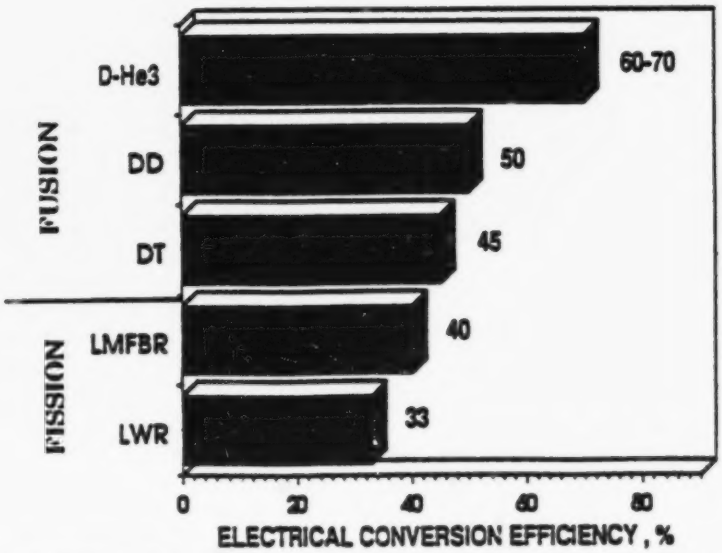

Figure 5. A comparison of overall conversion efficiencies of nuclear energy to electricity. The use of direct electrostatic or electromagnetic energy conversion schemes greatly enhances the performance of fusion devices.

IV-A. Efficiency

It is obvious that if only ~ 1% of the energy is released in neutrons, then the other ~ 99% is released as charged particles or photons. In linear magnetic fusion devices, where most of the energy leaks from the reactor in the form of highly energetic charged particles, one can convert their kinetic energy directly to electricity via electrostatic converters at ≥ 80%. This means that overall plant efficiencies of 60 to 70% are achievable. In toroidal magnetic devices, one can convert the synchrotron radiation emanating from the electrons (frequency ~ 3000 gigahertz) directly to electricity at roughly the same efficiencies (60-80%) through the use of rectenna. Depending on how the other forms of energy emitted from the plasma are utilized, the efficiency in toroidal devices may then be in the 40-60% range.

A comparison of the maximum conversion efficiencies that might be achieved by fission or fusion devices is shown in Figure 5. The important point to note is that fusion devices may increase the efficiency of fuel usage by a factor of 50 to 100% compared to fossil fuels or fission reactors. Such considerations are very important for thermal pollution in a terrestrial setting, but they are, in fact, critical to power plants that may operate in space. The rejection of heat in space is very, very costly.

IV-B. Radiation Damage

When high energy neutrons, such as the 14 MeV neutrons emitted from the DT reactions, run into structural reactor components, they can greatly reduce the mechanical performance of those components and induce significant long-lived radioactivity. With our present state of knowledge, it will be difficult to operate a fusion reactor for more than a few years before the metallic components become so brittle that they will have to be replaced. This requires shutting the reactor down, handling highly radioactive components, exposing workers to ionizing radiation, and generating large volumes of radioactive waste. Our best estimates at this time are that 2 to 3 reactor-years are about the limit for present day materials. Since reactors should operate for 30 or more years, such changeouts will occur 10 or more times during the lifetime of a typical DT fusion plant.

On the other hand, if we can reduce the neutron fraction to ~ 1% of the energy released in the D-He3 cycle, then the metallic components will last ~ 80 times longer than in a DT reactor. Such an extension is enough to completely obviate the necessity for component change due to neutron damage. This longer life will have profound economic and environmental benefits in a society based on the use of fusion energy.

IV-C. Reduced Radioactivity

Because of the much smaller number of neutrons, the induced radioactivity in the reactor walls will also be reduced by a factor of ~ 80. In today's DT fusion reactor designs, special materials have to be developed to avoid generating large amounts of high level wastes that must be placed in deep underground repositories. Conventional steels for example, would become so radioactive that 10's of tonnes per reactor-year could only be disposed of in one of the national deep repositories scheduled for operation near the turn of the century. On the other hand, these same materials would last the full 30 year

life of a D-He3 plant and still could be disposed of as low level class C waste buried in near surface disposal sites. If low activation steels are developed, then such alloys, after 30 years of operation could be buried along with medical waste in near-surface sites. Aside from the tremendous savings in cost, one would find that these D-He3 wastes would decay to benign levels in less than 100 years instead of the 1000's of years required for current fission and fusion devices.

IV-D. Safety

One of the most severe accidents that could occur in a DT fusion plant is the complete loss of coolant along with a complete breach of reactor containment. The afterheat in a DT reactor can be sufficient to release large amounts of tritium and radioisotopes from the reactor structure. At present, it is not known whether we can keep critical components from melting in a commercial DT reactor.

In a D-He3 reactor, two fundamental characteristics prevent such dire consequences. First, the afterheat (which comes directly from the neutron activation products) is so low that in the event of the most severe accident to be imagined, and if no heat leaked from the system (e.g., if the entire reactor was wrapped in a perfect thermally insulating blanket), the maximum temperature increase in a week would be ~ 500°C (still 1000°C below its melting point). Secondly, the tritium inventory in a D-He3 plant can be as little as 2 grams. The complete release of this tritium in a rain storm could still cause no more exposure to a member of the public living next to the D-He3 reactor than he or she normally receives from cosmic rays or radon gas in a year's time. *In other words, there is no possibility of an offsite fatality due to the release of all the volatile tritium radioactivity in a D-He3 fusion power plant and the consequences of such a release would be hard to detect among the populace.*

IV-E. Cost of Electricity

There are features of the D-He3 fuel cycle which strongly suggest that it will provide electricity more cheaply than a DT fusion power plant. These are

a) lower capital cost
b) lower operation and maintenance costs
c) higher efficiency
d) higher availability.

The first point is based on a comparison of two recent D-He3 reactor designs, Ra [3] and Apollo [4] to 17 previous DT reactor designs, most done by the same group with the same costing philosophies. The results of this comparison are shown in Figure 6. The direct capital cost of the Apollo-L D-He3 system is ~ 20-50% lower than comparable DT plants. The reason for this has to do with the greatly reduced balance of plant costs (i.e., that part of the power plant outside the fusion reactor) associated with conventional steam generators and turbines. It also has to do with the fact that D-He3 plants, which contain such low levels of T_2 and radioactivity, can use conventional construction grade material, thus avoiding the high nuclear-grade material costs associated with fission and probably with DT fusion reactors.

Because of the low radioactivity and because there should be no repair required from neutron damage, the number of plant personnel can be greatly reduced compared to a DT plant. The use of solid state electrical conversion equipment also will require less maintenance personnel.

The higher electrical efficiency will have a direct effect on the specific cost parameters. For example, the capital cost per kWe will be lower for the same thermal power, and the cost of heat rejection equipment (i.e., cooling towers) will be greatly reduced.

Finally, the ultimate cost of electricity, in mills per kWh, can be reduced if the plant stays on line for a larger fraction of its total lifetime. As stated previously, a DT power plant has to be shut down frequently to change neutron-damaged components. The duration of the down time will be adversely affected by the induced radioactivity and the problems associated with tritium contamination. It is also well known that plants which use a high-pressure steam cycle require, on average, on the order of 10-15% of their total life time to repair steam turbines and heat exchangers. The use of solid state conversion equipment should reduce that number similar to the way solid state TV sets are more reliable than those which used vacuum tubes.

IV-F. Shorter Time to Commercialization

The time from now to commercialization of D-He3 fusion could be shorter than the time to commercialize the DT cycle even if it takes longer to solve the remaining physics problems. The reason for this again lies in the low fraction of neutrons released in the D-He3 cycle and the need to develop a whole new class of metals and alloys to withstand the damage associated with the 14 MeV neutrons from the DT cycle. Conservative estimates of the cost to solve this problem include a materials test facility (1-2 B$ capital plus 10-15 years operating time requiring another 1-2 B$ in operating expenses), and a completely new blanket test facility in a demonstration power plant (3-4 B$ + 10-15 years and ~ 5 B$ operating costs) before one could get to a commercial system. Add to this significant sum the cost of an auxiliary technology program for 20-30 years beyond the solution of the physics problems (another 10-20 $B) and we can see that an additional ~ 30 $B and 30 years could be required to commercialize DT fusion after the successful DT physics operation in the ITER class of fusion devices in the year 2005.

On the other hand, if the ITER could be slightly modified (for less than 10% of its present cost) to ignite D-He3, then the same reactor could also be used to generate electricity in a demonstration reactor mode by 2005-2010. Since there is no need for a materials test facility nor for the need of developing breeding blankets, a new D-He3 commercial plant could be operational by the year 2015-2020, a full 15-20 years sooner than possible with the DT cycle.

V. Availability of Helium-3

V-A. Terrestrial Resources

It was commonly believed in the fusion community that after the questions of plasma physics have been solved, the next single largest barrier to the widespread study of the D-He3 reaction would be the lack of any large identified terrestrial source of helium-3. Studies by the SOAR (Space Orbiting

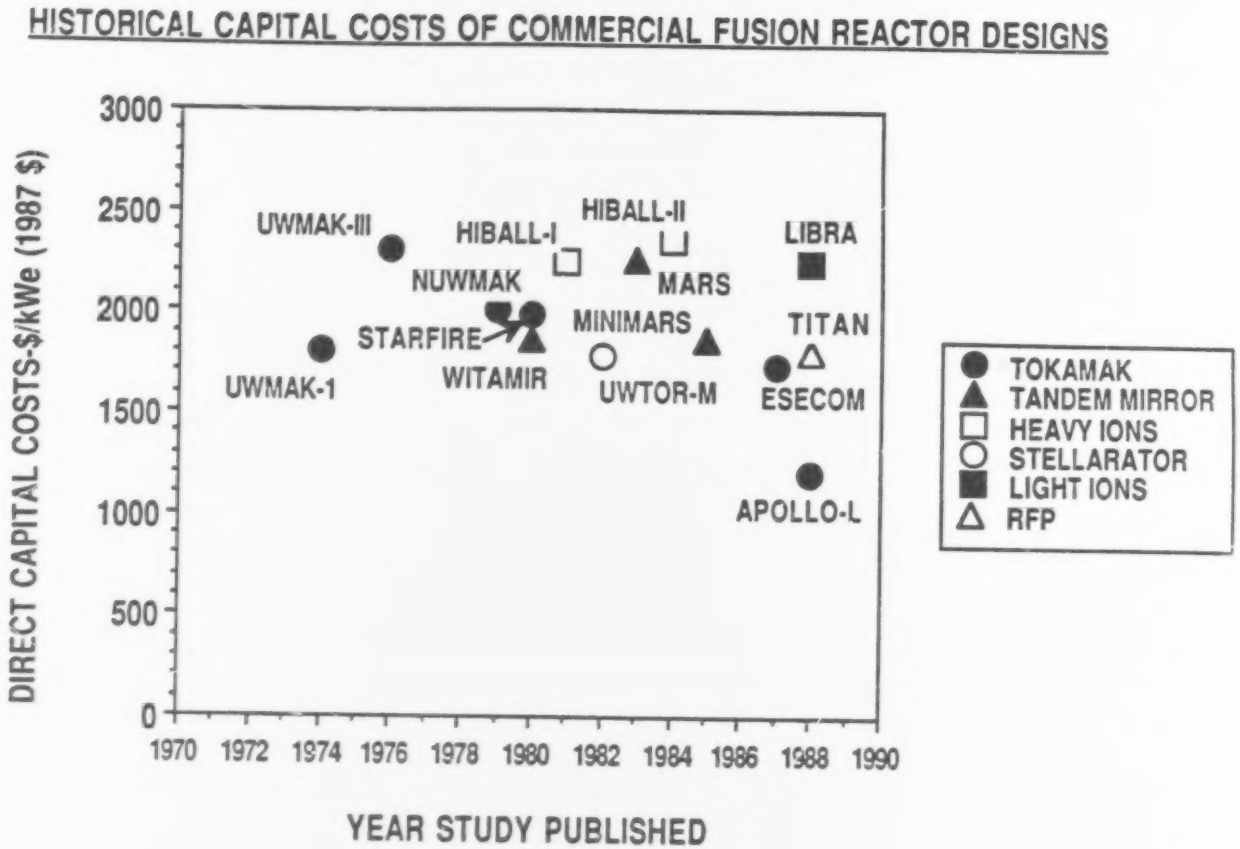

Figure 6. Historical Capital Costs of Commercial Fusion Reactor Designs

RESERVES OF He3 THAT COULD BE AVAILABLE IN THE YEAR 2000

SOURCE	CUMULATIVE AMOUNT (kg)	PRODUCTION RATE AFTER YEAR 2000 (kg/y)
PRIMORDIAL-EARTH		
● US HELIUM STORAGE	29	-----
● US NATURAL GAS RESERVES	187	-----
TRITIUM DECAY		
● US NUCLEAR WEAPONS	300	~15
● CANDU REACTORS	10	~2
TOTAL	>500	~17

Note:1 kg of He3 burned with 0.67 kg of deuterium yields 19 MW-y of energy

Table 1. Amounts of He3 That Could Be Available in the Year 2000

Advanced Reactor) concept at the University of Wisconsin in 1985 identified only small amounts of indigenous He3 on the Earth and a roughly equal-sized source from the decay of tritium ($t_{1/2}$ = 12.3 years) in the U.S. thermonuclear weapons program (see Table 1).

Most of the primordial He3, present at the formation of the Earth, has long since diffused out of the Earth and been lost in outer space. What is left in any retrievable form is contained in the underground natural gas reserves. Table 1 reveals that the total He3 content in the strategic He reserves stored underground amounts to only some 30 kg. If one were to process the entire United States known conventional natural gas reserves, another 200 kg of He3 might be obtained.

Another source of He3 on Earth is from the decay of tritium ($t_{1/2}$ = 12.3 years). When T_2 decays, it produces a He3 atom and a beta particle. Simple calculations of the inventory of T_2 in U.S. thermonuclear weapons shows that if all the He3 were collected, some 300 kg would be available by the year 2000. Presumably about the same amount of He3 would be available from the weapons stockpile of the USSR. The equilibrium production of He3 (assuming no future change in weapons stockpiles) is around 15 kg per year in each country. It may seem strange to rely on a by-product from weapons for a civilian application, but the He3 commercially available today is from just such a process. One can purchase up to 1.38 kg of He3 per year directly from the U.S. government (10,000 liters at STP) all of which comes from T_2 decay. Obviously, considerably more is available, and simple calculations of the tritium production from U.S. facilities at Savannah River indicate that tritium production could be in the 10-20 kg per year range. This would imply an "equilibrium" He3 production rate of ~ 10-20 kg/year minus losses in processing.

One could also get smaller amounts of He3 from the T_2 produced in the heavy water coolants of Canadian CANDU reactors. This could amount to 10 kg of He3 by the year 2000, and He3 will continue to be generated in these plants at a rate of ~ 2 kg per year thereafter.

It should be noted again that 1 kg of He3, when burned with 0.67 kg of D, produces approximately 19 MW-y of energy. This means that by the turn of the century, when there could be several hundred kg's of He3 at our disposal, the potential exists for several thousand MW-y of power production. The equilibrium generation rate from T_2 resources alone could fuel a 300 MWe plant indefinitely if it were run 50% of the time.

Clearly, there is enough He3 to build an Experimental Test Reactor (ETR) (a few hundred MW's running 10-20% of a year) and a demonstration power plant of hundreds of MWe run for many years. This could be done without ever having to leave the earth for fuel. The real problem would come when the first large (GWe) commercial plants could be built around the year 2015.

V-B. <u>What and Where are the He3 Resources on the Moon?</u>

Wittenberg et al. [5] showed in September 1986 how the He3, first discovered on the Moon by the Apollo-11 mission, could be utilized in a fusion economy. Since that time, work at the University of Wisconsin has elaborated on the original idea. A few highlights will be summarized here.

The origin of lunar He3 is from the solar wind (i.e., the charged particles leaking from the sun and "blowing" on the rest of the bodies in the solar system). Using data which showed that the solar wind contains ~ 4% helium atoms and that the He3/He4 ratio is ~ 480 appm, it was calculated that the surface of the Moon was bombarded with over 250 million metric tonnes in 4 billion years. Furthermore, because the energy of the solar wind is low (~ 3 keV for the He3 ions), the ions did not penetrate very far (< 0.1 micron) into the surface of the regolith particles (lunar soil). The fact that the surface of the Moon is periodically stirred, as the result of frequent meteorite impacts, results in the helium being trapped in soil particles to depths of several meters.

Analysis of Apollo and Luna regolith samples revealed that the total helium content in the Moon minerals ranges from a few to 70 wtppm (see Figure 7). The higher concentrations are associated with the regolith on the old titanium-rich basaltic Maria of the Moon, and the lower contents are associated with the Highland rocks and Basin Ejecta. Clearly the higher concentrations are in the most accessible and minable material. Using the data available, it is calculated that roughly a million metric tonnes of He3 are still trapped in the surface of the Moon [5] (see Table 2).

The next step is to determine the most favorable location for extracting this fuel. Cameron [6] has shown that there is an apparent association between the helium and TiO_2 content in the samples. Assuming that this is generally true, he then examined the data on spectral reflectance and spectroscopy of the Moon which showed that the Sea of Tranquility (confirmed by Apollo 11 samples) and certain parts of the Oceanus Procellarium were particularly rich in TiO_2. It was then determined, on the basis of the large area (190,000 km^2) and past U.S. experience, that the Sea of Tranquility would be the prime target for initial investigations of lunar mining sites. This one area alone appears to contain more than 8,000 tonnes of He3 to a depth of 2 meters. Backup targets are the TiO_2-rich basalt regolith in the vicinity of Mare Serenitatis sampled during Apollo 17 and areas of high-Ti regolith, indicated by remote sensing, in Mare Imbrium and other mare of the lunar western hemisphere [6].

V-C. How Would the He3 be Extracted?

Since the solar wind gases are weakly bound in the lunar regolith it should be relatively easy to extract them. Pepin [7] found (Figure 8) that heating lunar regolith caused the He3 to be evolved above 200° C and by 600° C, approximately 75% of the He gas could be removed.

There are several methods by which the He could be extracted and a schematic of one approach is shown in Figure 9. In this unit, the loose regolith, to a depth of 60 cm, is scooped into the front of the robotic unit. It is then sized to particles less than 100 microns in diameter (about 65% of the regolith) because there seems to be a higher concentration of solar gases in the smaller particles (presumably because of the high surface to volume ratio). After beneficiation, the concentrate is preheated by heat pipes [4] and then fed into a solar-heated reaction chamber. At this point, it is anticipated that heating to only 600 or 700°C is required, and the volatiles (H_2, He4, He3, H_2O, C compounds, N_2) are collected. The spent regolith concentrate is discharged through recuperative heat exchangers to recover 90%

HELIUM-3 CONTENT OF LUNAR REGOLITHS

LOCATION	% LUNAR SURFACE	AVE. HELIUM CONC. wtppm	TONNES He3
MARIA	20	30	600,000
HIGHLANDS & BASIN EJECTA	80	7	500,000
		TOTAL	1,100,000

Table 2. Helium-3 Content of Lunar Regoliths

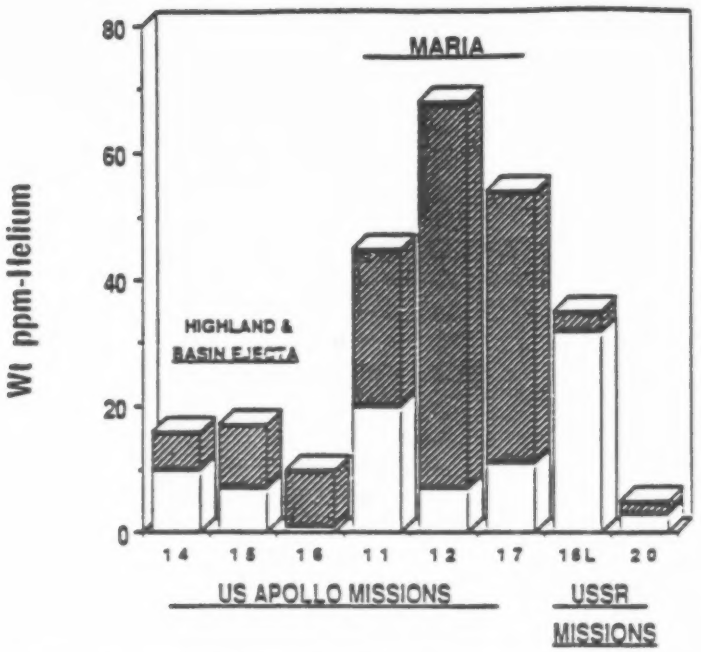

Figure 7. Range of helium concentration measured in U.S. Apollo and USSR Luna samples. Cross-hatched region gives range.

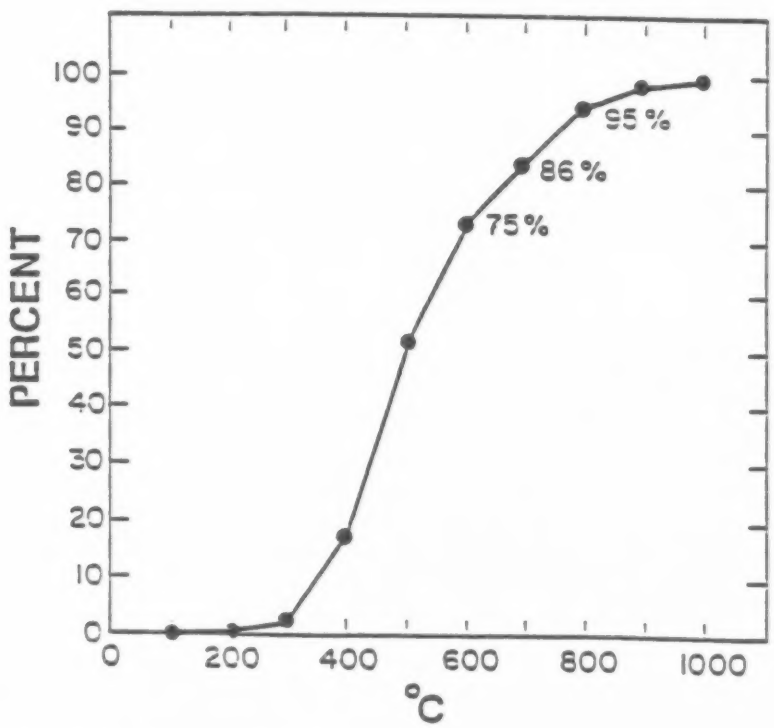

Figure 8. Evolution of He3 from lunar regolith as measured by Pepin [3] in 1970.

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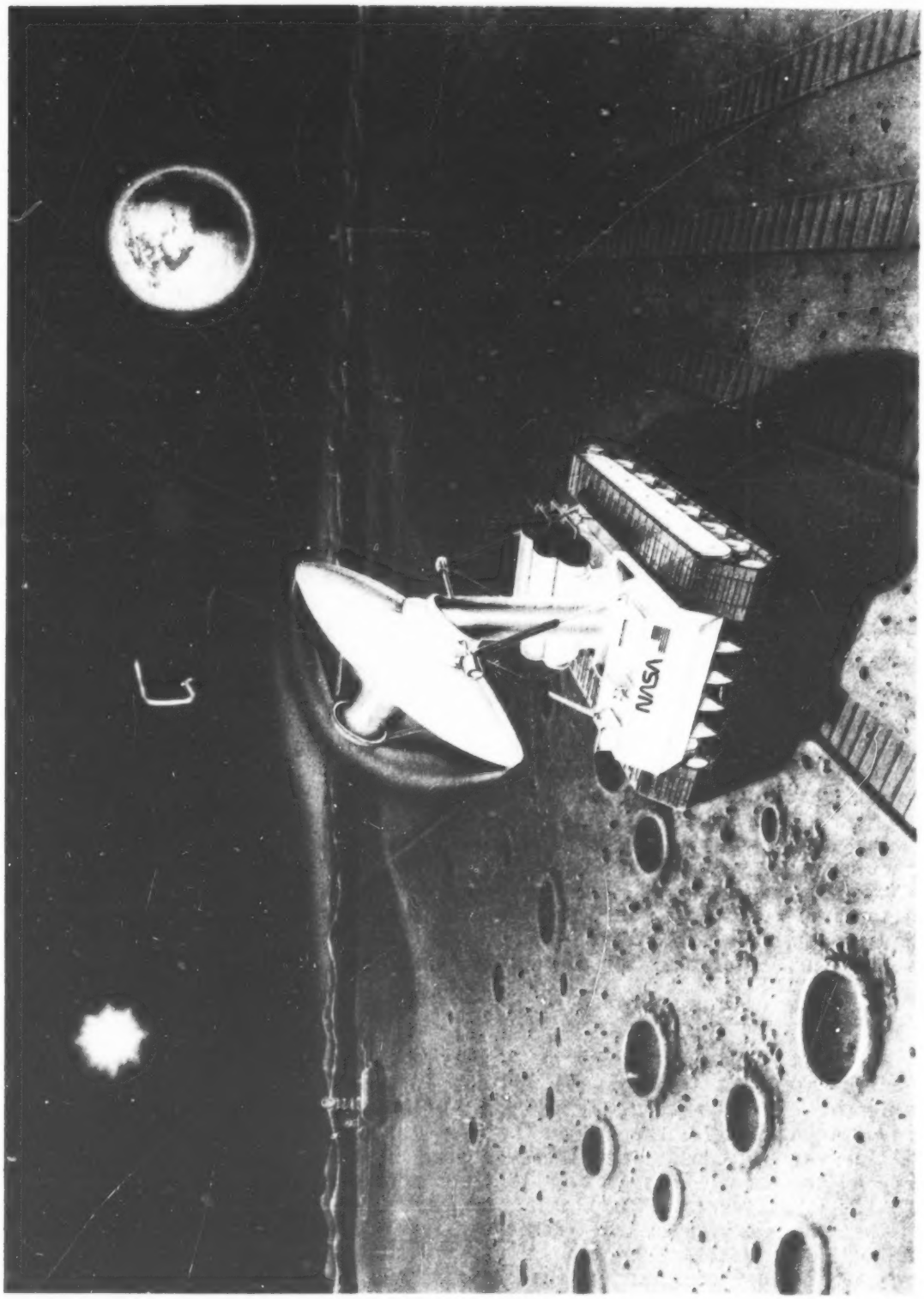

Figure 9. Design of lunar vehicle to extract He3 from regolith using direct solar radiation.

of its heat. The spent regolith is finally dropped off the back of the moving miner. Note that in the 1/6 gravity environment, relatively little energy is expended lifting material.

Of course, this solar energy-driven scheme would only work during the lunar day, but orbiting mirrors, nuclear reactor heat from a mobile power plant, or indirect radiofrequency (RF) heating from electricity generated at a central power plant on the Moon could extend the operating time. Alternative schemes are being examined through parametric analyses of such variables as particle size vs. temperature vs. yield, mining depth vs. He3 concentration vs. particle size distribution, manned operation vs. robotic operations vs. maintenance costs, mechanical particle separation vs. gaseous particle separation vs. yield, solar vs. nuclear power, etc.

Once the lunar volatiles are extracted, they can be separated from the helium by isolation from the lunar surface and exposure to outer space (< 5 K) during the lunar night. Everything except the helium will condense and the He3 can be later separated from the He4 by superleak techniques well established in industry [5].

For every metric tonne (1000 kg ≈ 2200 pounds) of He3 produced, some 3100 tonnes of He4, 500 tonnes of nitrogen, over 4000 tonnes of CO and CO_2, 3300 tonnes of water, and 6100 tonnes of H_2 are produced (see Figure 10). The H_2 will be extremely beneficial on the Moon for lunar inhabitants and for propellants. Transportation of that much H_2 to the Moon, even at 1000 $/per kg (about 1/10 of present launch costs), would cost ~ 6 billion dollars. As noted below, the He3 itself could be worth as much as ~ 2 billion dollars per tonne. Of the other volatiles, the N_2 could also be used for plant growth, the carbon also for plant growth, for manufacturing or atmosphere control, and the He4 for pressurization and as a power plant working fluid. Oxygen, either from the water or carbon compounds, could be used for interior atmospheres or for fuel in rockets from the Moon.

The environmental impact to the Moon as a result of this type of volatile extraction would be minimal. For example, there would be "tracks" on the Moon and the surface would be smoothed and slightly "fluffed up" as the spent regolith is redeposited. The vacuum at the lunar surface might also be temporarily affected but, due to the low gravity level, most of the gas atoms will leave the surface of the Moon during the lunar day.

V-D. How Much is the He3 Worth?

While it is hard to anticipate the cost of energy in the future, one can anticipate what we might be willing to pay for fuel based on today's experience. First of all, it is worthwhile to get a feeling for how much energy is contained in the He3 on the Moon. If the ultimate resource base is 1 million metric tonnes, then there is some 20,000 TW-y of potential thermal energy on the Moon. This is over 10 times more energy than that contained in economically recoverable fossil fuels on earth. This amount of energy is also 100 times the energy available from economically recoverable U on earth burned in Light Water Reactors on a once through fuel cycle or roughly twice the energy available from U used in Fast Breeder Reactors.

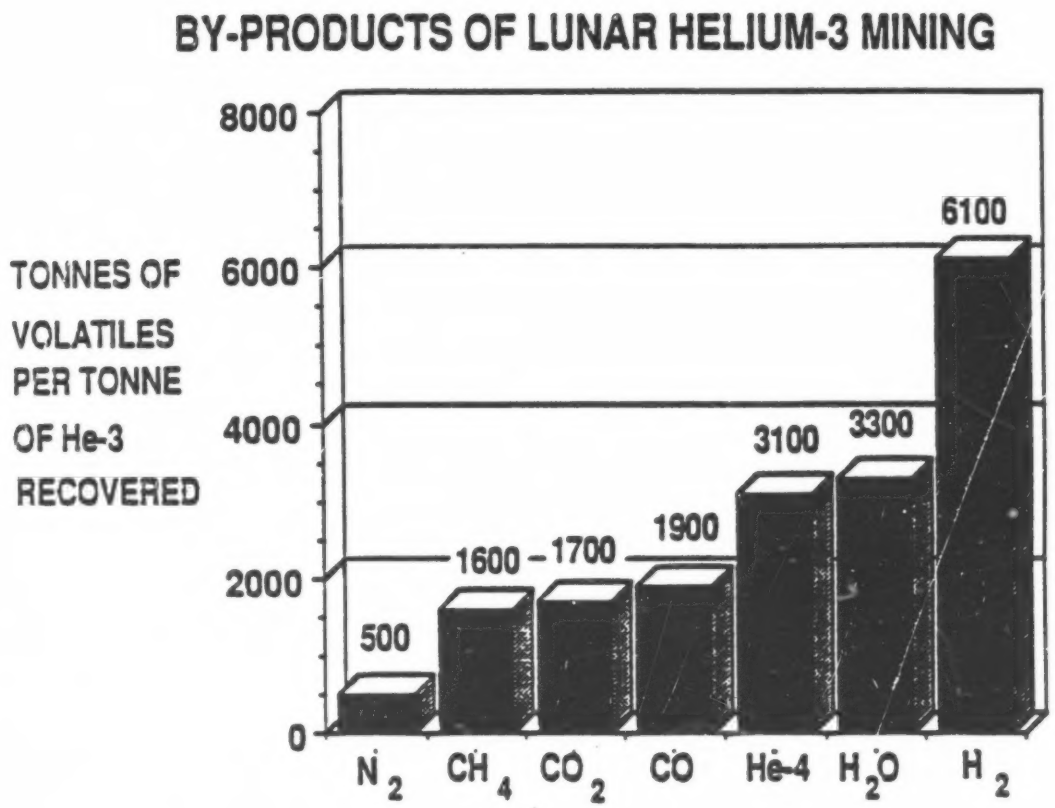

Figure 10. By-Products of Lunar Helium-3 Mining

The second point is that only 25 tonnes of He3, burned with D_2 in a Ra [3] type reactor, would have provided the entire U.S. electrical consumption in 1987 (some 285,000 MWe-y). The 25 tonnes of condensed He3 could fit in the cargo bay of a spacecraft roughly the size of the U.S. shuttle.

A third point is that in 1987, the U.S. spent over 40 billion dollars for fuel (coal, oil, gas, uranium) to generate electricity. This does not include plant or distribution costs, just the expenditure for fuel. If the 25 tonnes of He3 just replaced that fuel cost (while the plant and distribution costs stayed the same) then the He3 would be worth approximately 1.6 billion dollars per tonne. At that rate, it is the only thing we know of on the Moon which appears to be economically worth bringing back to earth.

An obvious question at this point is how much does it cost to obtain He3 from the Moon? The answer to that depends on three things:

(1) Will the U.S. develop a Moon base for scientific or other mining operations without the incentive of obtaining He3?
(2) If the answer to the above question is yes, then how much will the incremental costs of mining He3 be after manned lunar bases are already in place?
(3) How will the benefits of the side products be treated? For example, will one be able to "charge" the lunar settlement for the H_2, H_2O, N_2, He, or carbon compounds extracted from the lunar regolith?
(4) Will the ultimate export of volatiles to a Mars settlement add a significant rate of return to the enterprise?

The answer to question 1) may be yes. In a 1987 report to NASA, by the Ride Commission [10], it was stated that one of the 4 major future programs in NASA should be a return to the Moon and the establishment of a manned base early in the 21st century. This recommendation was made without any reference to the He3 mining possibilities. Furthermore, President Bush, called for a return to the moon on July 20, 1989 during the celebration of the 20th anniversary of the Apollo 11 landing on the moon. At this time, it appears reasonable to assume that the cost of returning to the Moon will be borne by the U.S. government or by an international entity as a general investment in science.

The answer to question 2) cannot be given at this time but should be the subject of study in the near future. It appears that, based on the mobile mining concept described earlier, that the equipment required to produce 25 tonnes per year could be transported to the Moon for well under 30 billion dollars (e.g., at 1000 $/kg this would allow 30,000 tonnes to be transported to the Moon). Operational costs should be well under a billion dollars per year even if no use of lunar materials is allowed. The above costs are to be compared to 500-1000 B$ in revenue from the He3 mining during the useful life of the equipment.

The possibilities of "selling" the by-products of the He3 to lunar colonies is also very intriguing. The by-products from mining just one tonne of He3 would support the annual lunar needs (properly accounting for losses through leakage and through waste recycling) of [11]:

1,400 people for N_2 (food and atmosphere)
22,000 people for CO_2 used to grow food
45,000 people for H_2O.

If the cost of transporting the equipment to extract these volatiles from the lunar regolith is written off against the savings in sending up life support elements such as H_2, N_2, or carbon for manned lunar bases, then it is possible that the cost of He3 may in fact be negligible. If that were true then the cost of electricity from D-He3 fusion power plants would indeed be much cheaper than from DT systems and possibly even from fission reactors (without taking credit for all the environmental advantages of the D-He3 fuel cycle).

To answer the question posed by the title of this section, it appears that a realistic figure for the worth of He3 on the earth is ~ 1 or 2 billion dollars per tonne (1000 $/g). This should allow D-He3 fusion plants to be competitive with DT systems and provide adequate incentive for commercial retrieval from the Moon. This latter point is currently the subject of the Enterprise study conducted by NASA.

V-E. What is the Current Attitude Toward He3 Development?

The current domestic and international policy environment may require significant modification to enhance the development of helium-3 fusion power on earth or helium-3 mining on the Moon. Policy issues that may affect the ultimate availability of helium-3 fusion power include the following:

1. U.S. Commitment: There is no firm commitment by the U.S. Department of Energy to the development of commercial helium-3 fusion power or by NASA to the creation of a space and lunar infrastructure that would support such a commitment. However, the two agencies now meet on a regular basis to coordinate research into D-He3 fusion and it is possible that such efforts could provide the basis for a coordinated program.

2. Soviet Commitment: There have been strong indications that, beyond a research interest in helium-3 fusion, the Soviets have focused their deep space related development on Mars rather than on lunar resources. However, recent public statements by Soviet space and fusion researchers at the Kurchatov Institute in Moscow suggest that D-He3 fusion and lunar He3 are of increasing interest to them.

3. U.S.-Soviet Cooperation: The lack of long range U.S. goals related to helium-3 fusion and the apparent focus of long range Soviet goals on Mars suggest that near term cooperation related to helium-3 mining on the Moon is unlikely unless a specific new stimulus is provided.

4. European Potential: 1992 will see a major step toward a United States of Europe with the technical and economical potential to be a major player in helium-3 fusion and lunar resource development. Indeed, Europe will have the potential to "go it alone" even though it may or may not decide to use that capability. It is not clear that the rest of the world has fully recognized this looming change in Europe's status as a "Great Power." In any case, preliminary investigations of the use of He3 in NET, the Next European Torus, have been conducted and experiments in the European JET devise have released 100 kW of thermonuclear power from the D-He3 reactor, a world record!

5. Asian Potential: Several Pacific rim nations, in aggregate, also have the technical and economic potential to be a major player in helium-3 fusion and lunar resource development. This potential will be enhanced if China becomes associated with these nations. The difficulties of Asian cooperation, however, appear to significantly exceed those of Europe.

6. Third World Desires: The Third World nations (i.e., Group of 77) can be anticipated to push for inclusion in the distribution of economic benefits from any helium-3 enterprise and possibly in the actual management of a lunar mining enterprise.

7. International Cooperation: Existing international arrangements (e.g., the Moon Treaty and INTELSAT) may provide the basis for future cooperation in helium-3 fusion development and lunar helium-3 production. In this context, the ITER agreement between the United States, the USSR, Japan, and the European Community, with China and Canada in associate status, may provide the basis for initiating such cooperation.

8. Environmental Protection: A qualitative net assessment of the environmental benefits of helium-3 fusion appears to be strongly in favor of its development when the full environmental impact of fossil and fission fuels is considered. However, the general emotional resistance to the development of nuclear power in the U.S. may prolong decision making related to helium-3 fusion.

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16. Abstract

The Lunar Energy Enterprise Case Study Task Force was formed to determine the economic viability and commercial business potential (1) of mining and extracting ^{3}He from the lunar soil for use on Earth in fusion reactors, (2) of the Solar Power Satellite (SPS) and (3) of the Lunar Power Station (LPS) because they involve the use of lunar materials and could provide energy for lunar-based activities. The Task Force considered: (1) the legal and liability aspects of the space energy projects, (2) the long-range terrestrial energy needs and options, (3) the technical maturity of the three space energy projects, and (4) their commercial potential. The use of electricity is expected to increase, but emerging environmental concerns and resource availability suggest changes for the national energy policy. All three options have the potential to provide a nearly inexhaustible, clean source of electricity for the U.S. and worldwide, without major adverse impacts on the Earth's environment. Assumption by industry of the total responsibility for these energy projects is not yet possible. Pursuit of these energy concepts requires the combined efforts of government and industry. The report identifies key steps to the development of these concepts and to an evolving industrial role.

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